A Comparison of Technical and Environmental Merits of Producing Bio-Ethanol and Bio-Methane from Waste Paper Sludge

MSc Thesis

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ABSTRACT

The pressing need for alternative methods of waste management in developing countries has led to increased interest in energy recovery from waste. However, owing to the high proportion of wet organic waste, it will be necessary to take material-specific approaches going beyond bulk incineration. Life Cycle Assessments (LCAs) have shown that there is a large potential in bio-energy production from waste papers and cellulosic waste sludge, however, it is still unclear whether it would be more feasible to convert the mostly wet non-recyclable waste paper to bio-methane or to bio-ethanol.

The primary objective of this study was to evaluate the technical and environmental feasibility of converting waste paper sludge to bio-ethanol and bio-methane for application as a vehicle fuel or for the generation of electricity. The focus of this study was on the conversion of *waste paper sludge* (WPS) in particular, which is generally sent directly to landfill and rarely treated. The following hypothesis was put forward:

> *Relatively uncontaminated forms of non-recyclable paper will become an attractive feedstock for commercial fuel bio-ethanol production, especially where flex-fuel vehicles are wide*-spread – however, this will not represent the most energy-efficient or environmentally friendly energetic usage of this type of waste paper.

A Life Cycle Assessment (LCA) approach was chosen to evaluate and compare ethanol production for the use in a flex-fuel vehicle to both ethanol-based and biogas-based electricity alternatives within a South African context, which displays a very coal-intensive economy. Conversion of WPS to ethanol or biogas for cogeneration is preferable to producing ethanol for use in flex-fuel vehicles.

Studies involving the conversion of WPS to biogas were scant in the literature; however waste paper proved an attractive carbon-source for biogas production, which motivated experimental work involving WPS. The following hypothesis was put forward:

> *Forms of non-recyclable and non-recoverable paper which are more contaminated will co-digest well in anaerobic digesters set up to recover energy from waste and reduce volumes for disposal, boosting gas yields per unit of digester volume, especially when used to adjust carbon to nitrogen ratios.*

Contamination was not itself investigated here, but a co-digestion with a protein-containing substrate was used to represent the presence of other potentially trouble-some substances. Based on the bio-chemical methane potential (BMP) assays involving the co-digestion of WPS with nitrogen-rich substrates, abattoir and fish waste (AW and FW, respectively), it can be concluded that increased bio-methane yields per g VS_{FED} can be achieved through co-digestion. However, the extent of these improvements is dependent on the seed inoculum and particular material used. On the other hand, co-digestion consistently displayed improvements to the overall stability of the system.

It is recommended that the a selection of the assay mixtures be scaled-up to 2 L batch-fed reactors as the ideal conditions of the BMP analyses were not always realistic at a large-scale. Analyses such as the change of pH, VFAs, COD and VS would provide a better understanding of the biogas systems.

The findings of this dissertation are in agreement with that of earlier work referred to in the literature review that a focus on liquid bio-fuels is too narrow, from an environmental aspect as the biogas options have been shown to be competitive with the ethanol-based options. In a coal-intensive economy, such as that of South Africa, significant environmental improvements are possible by replacing coal-based energy products.

Biogas technology should therefore be considered more seriously within “bio-energy” discussions.

Finally, for a fuller, more complete sustainability analysis, it is recommended that the research be extended to include the social and economic implications of the bio-energy from waste paper systems. This should include a comparison to the “business-as-usual” scenarios of the traditional fossil-energy based electricity and gasoline.

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ABBREVIATIONS

Symbol	Description
WtE	Waste-to-energy
BEfW	Bio-Energy from Waste
AD	Anaerobic digestion
BMP	Bop-Chemical Methane Potential
LHV	Lower heating value (MJ/ m3 or MJ/ kg)
GHG	Green house gases
RPS	Recycled paper sludge
MWP	Mixed waste paper
OCC	Old corrugated cardboard
TS	Total solids
VS	Volatile solids
AW	Abattoir waste
FW	Fish waste
PM2	Virgin-derived waste paper sludge from Nampak Plant PM2
PM4	Recycled paper sludge from Nampak Plant PM4
WPS	Waste paper sludge
SSF	Simultaneous saccharification and fermentation
CHP	Co-generation of heat and power
E-FFV	Ethanol-based flex-fuel vehicle
EE	Ethanol-based electricity
EE-HI	Ethanol-based electricity with heat integration
MBE	Mono-digested WPS to biogas fro electricity
MBE-HI	Mono-digested WPS to biogas for electricity with heat integration
CBE	Co-digested WPS to biogas for electricity
CBE-HI	Mono-digested WPS to biogas for electricity with heat integration

Symbol	Description
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
AP	Acidification Potential
EP	Eutrophication Potential
GWP	Global Warming Potential
POP	Photochemical Oxidation Potential
FWT	Fresh Water Aquatic Potential
HTP	Human Toxicity Potential

1 INTRODUCTION

This chapter introduces the context for the study, followed by a statement of the problem and objectives. The key questions and scope are then presented. The chapter closes off with an overview of the dissertation structure.

1.1 Background

Fossil fuels play a large role in meeting the requirements of South Africa's energy-intensive economy, with coal and imported crude oil contributing to 70% and 18% of the country's primary energy, respectively. At the same time, there is a growing struggle to effectively manage the large volumes of municipal solid waste (MSW) being generated and disposed of in landfill sites (AGAMA Energy Ltd, 2006).

Waste paper alone contributes a large portion of total solid waste volumes, of the order of 20%for the case of Cape Town (Greben, 2009; PRASA, 2010). Although recycling is preferable over disposal in landfill or incineration, a significant portion of recyclable waste paper is simply not recovered, often because some streams of waste paper are strongly contaminated e.g. with putrescible material, rendering them non-recoverable. Also, the saturation of recycling plants in Cape Town has led to disposal of a significant portion of the reusable paper in landfill sites. This often results in contamination as well, thus rendering material unsuitable for extraction by scavengers operating on landfill sites. The recycling plants themselves also produce large volumes of recycled paper sludge (RPS), as the degradation of cellulosic fibres during processing limits the number of times paper can be recycled. In addition to this, certain paper products, such as waxed paper, are not compatible with the current methods of recycling and are either incinerated or sent immediately to landfill, if not reused.

Life Cycle Assessments (LCAs) have shown that there is a large environmental improvement potential in redirecting such waste papers and cellulosic waste sludges

from landfill disposal to energy production (Finnveden, 2004; Petrie *et al*, 2008). Waste papers are often recovered in moist form and sludge is usually moist. Whilst incineration is possible even for wet materials and energy-neutral at about 10% solids content, their expense and technical intricacy have thus far prevented them from being seriously considered for municipal waste treatment in developing country contexts. Cellulosic ethanol production and anaerobic digestion for bio-methane production are therefore considered as an alternative to such out-of-reach thermal technologies.

1.2 Problem statement and objectives of this study

Whilst it is increasingly becoming clear that developing cities, particularly African ones, need to consider introducing energy recovery into their waste management strategies, it also appears that owing to the high proportion of wet organic waste it will be necessary to take material-specific approaches going beyond bulk incineration. In this regard, it is still unclear whether it would be more feasible to convert the mostly wet non-recyclable waste paper to bio-methane or bio-ethanol.

The central objective of this dissertation therefore is to deliver new insights for the "energy from waste" knowledge sector, particularly regarding the process technologies available for energy recovery from non-recyclable wet paper wastes, their relative performance, as well as the usefulness and environmental effectiveness of the new energy products.

1.3 Key questions

The key questions addressed by this dissertation are as follows:

i. What energy yields can be achieved for bio-methanation and for hydrolysis-fermentation to fuel bio-ethanol of wet, uncontaminated non-recyclable paper waste?
ii. What are the efficiencies of bio-ethanol and bio-methane conversion to power generation?
iii. What factors, other than energy yield, should be considered in developing a preference?
iv. How does contamination affect performance and preference?

1.4 Scope of the study

This particular study is shaped by the context of developing cities with little infrastructure to support the large volumes of waste being generated. Cape Town, which currently disposes of its waste in formal landfills, is an example of such a city. The focus of this study is on conversion of the paper fraction of the waste to energy, in particular on the *sludge* from *paper recycling* ("recycled paper sludge", RPS), which is sent directly to landfill and rarely treated.

The study is based in the greater Cape Town area as it is a suitable example of a developing world city. The assessment considers the technical and environmental impacts of technologies for converting waste paper feedstock to bio-energy in various scenarios and, based on the results, will propose the most appropriate management of such waste in various contexts.

1.5 Summary of the dissertation structure

This dissertation is divided into four parts, opening with the *Prelude*, which provides the reader with the context to the problem that is to be addressed in this dissertation as well as an overview of how this is to be done. This leads into both the *Experimental Part* and *Modelling Part.* The former, which consists of two chapters, also feeds back into the *Modelling Part*. The dissertation ends with the *Interpretation Part*, which consists of two chapters. A graphical depiction of the thesis structure is presented below (Figure 1-1) followed by a brief description of the subsequent chapters.

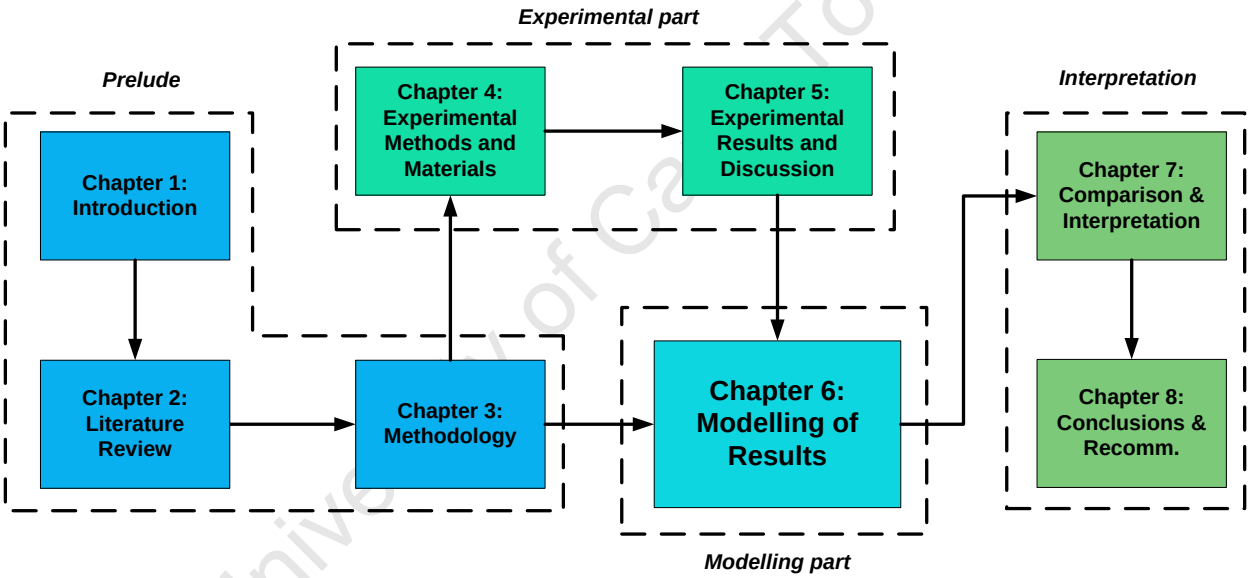


Figure 1-1: Schematic representation of the thesis structure

Chapter 2 delivers an organisation of the applicable literature material and critically evaluates the findings of previous work to identify gaps and inconsistencies. Through this the nature of the problem is identified in more detail, to form the basis for the development of the subsequent chapters.

Chapter 3 develops the hypotheses to be tested, and proceeds to develop the methodology followed to address the defined problem.

Chapter 4 describes the design of the experimental work, together with a detailed description of the tools and techniques required to apply the design.

In, **Chapter 5**, the results of the experimental work are presented. This also includes a detailed discussion and concluding remarks.

In **Chapter 6**, the scenarios to be assessed are defined and modelled to generate the data necessary for comparative analysis.

Chapter 7 presents the results of the comparative analysis, and provides a detailed discussion and interpretation of these results.

Chapter 8 concludes the dissertation by compiling and presenting the overall findings. Recommendations, based on these findings, are put forward.

2 LITERATURE REVIEW

Based on the problem statement and objectives of the study, key questions were developed to aid the process of the review of literature. In attempting to answer these questions, within the defined scope, gaps in the literature were identified and so helped in the development of the hypotheses, providing direction for the steps which follow.

The first section of the literature review provides an overview of the status of energy in Cape Town. This is followed by a review of the potential biomass sources available in the waste paper fraction of the MSW and current technologies available for the conversion of these wastes to energy. Based on the data collected from literature, a preliminary assessment of the energy potential of a selection of the identified biomass sources is presented and compared for the selected bio-energies. The chapter closes off with an assessment of recent Life Cycle Assessments (LCAs) on "waste-to-energy" systems.

2.1 Renewable energy in South Africa and in Cape Town

South Africa's energy production is dominated by coal, contributing to 86% of its total electricity production. This is followed by nuclear power (5%), gas (4%) and various other sources, such as renewable hydro and pumped storage (Pegels, 2010). In addition to this, approximately 30% of the country's domestic fuel-oil demand is met through the conversion of coal and gas to transportation fuels (Beck, 2011).

South Africa's dependency on coal has placed it at the 13th largest CO_2 emitter in the world. Much of the coal used is of a low quality and also easily accessible, resulting in a low input cost. In addition to this, national coal reserves are plentiful and pressure on supplies is not likely to be felt any time soon, with peak production only expected around 2070 (Winkler, 2006b).

Compared to the total energy used in South Africa, the use of renewables is still very small; a far cry from the target set forth by the Department of Minerals and Energy (DME) in 2003. The White Paper on renewable energy set a target of an annual 10,000 GWh renewable energy contribution to the final energy consumption by 2013, with the principle sources being biomass, wind, solar and small-scale hydro. To date only 3% of this target has been successfully installed (Pegels, 2010).

In addition to this, a renewable electricity target of 10% by 2020 was set forward in an Energy Report released 2003 by the City of Cape Town describing the status of energy provision and utilisation at the time. This correlates to a total of ~15 PJ/a of renewable energy consumption in 2020 (Nissing and von Blottnitz, 2007).

In 2007, the South African government produced its Long-Term Mitigation Scenarios (LTMS) illustrating possible greenhouse gas (GHG) emission pathways for the period 2003 to 2050. The first scenario, "Growth without constraints", allows for unlimited economic growth which foresees emissions quadrupled by 2050 (Pegels, 2010). This is neither plausible nor ideal.

The second scenario, "Required by Science", analyses how South Africa's GHG emissions could be reduced by 30 - 40% between 2003 and 2050.This is achieved through the implementation of various mitigation actions at various "levels" within the scenario (further detailed in Winkler, 2007). The "required by science" scenario assumes a 15% renewable electricity share by 2020 and 27% by 2030 (Pegels, 2010), as one of the major interventions, referred to as "wedges". Included within the renewable options to meet demand are hydro, wind, solar, biomass and landfill gas technologies, PV, bagasse, and pulp and paper.

The remainder of this section gives an overview of the current state of the energy system in the City of Cape Town in terms of demand and supply.

2.1.1 Current energy system of Cape Town

Based on Winkler *et al*'s (2006a) projected energy consumption of a business-as-usual scenario in Cape Town, the overall energy consumption currently sits at ~130 PJ/a. The largest energy demands are accounted for by the transportation sector, industry and household demands (Figure 2-1). Commerce and government only account for 8% of the city's energy consumption.

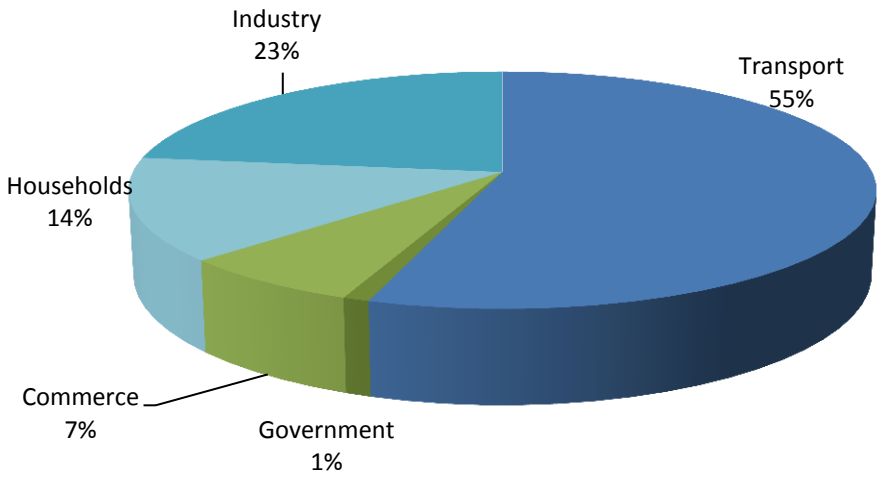


Figure 2-1: Energy demand per sector in Cape Town (Winkler et al, 2006a)

The energy consumption with respect to various energy carriers is depicted in Figure 2-1. Petrol (38%) and diesel (18%) account for the majority of the energy consumption due to the city's high transport requirements. The city's electricity needs account for 33% of the total energy consumption, owing to the electricity usage of households and the industry sector; whereas the use of renewable wood accounts for only 1% of Cape Town's total energy consumption (Nissing and von Blottnitz, 2007).

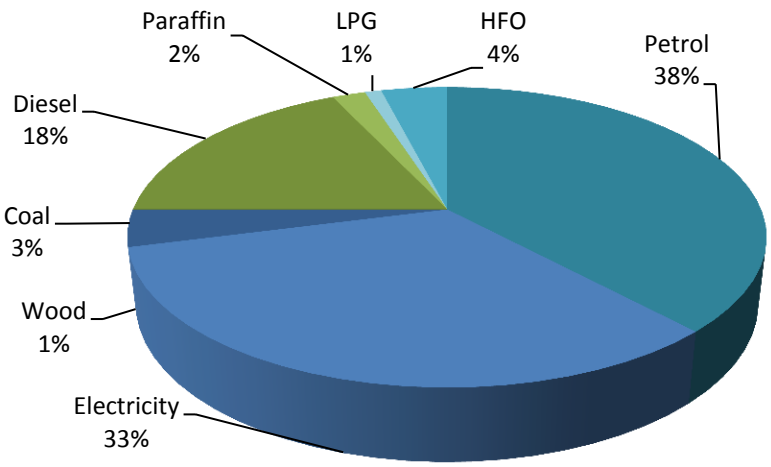


Figure 2-2: Energy carrier consumption in Cape Town (compiled using Nissing & Von Blottnitz, 2007)

The current electricity distribution within the Cape Town metropolitan area is split between the City and the Eskom national electricity grid, the latter providing 98% of the electricity sold in Cape Town (CoCT, 2005). Approximately 95% of the electricity imported from Eskom's national grid is generated at its coal-generated plant in the north of the country, 5% is of nuclear capacity (Koeberg) and a small amount is hydro sources. Electricity contributes to 68% of the City's CO_2 emissions on account of the imported coal-based electricity (CoCT, 2005).

As previously mentioned, the liquid fuel supply in South Africa's is dominated by imported crude oil which is processed at refineries around the country. In addition to this, liquid fuels are also generated through the synthetic processing of coal at Sasol, and gas deposits the PetroSA Mossel Bay Refinery (CoCT, 2005).

2.1.2 City level developments in Energy-from-Waste

Based on an assessment of the State of Energy in Cape Town numerous issues were identified within the energy sector. These issues, based on the City's stated priority areas and key national and international obligations, directly informed the five Energy and Climate Change Strategy Visions and the goals associated with them (CoCT, 2005).

This strategy envisions the City of Cape Town meeting its energy needs in a *sustainable* way and thus fulfilling its constitutional and global obligations. The main goal is the increased contribution of renewable and clean energy to the energy mix to reduce the current dependency on fossil energy sources, for both electricity and transport fuels, starting with the most financially viable options (CoCT, 2005).

Considerable scope therefore exists in Waste-to-Energy (WtE) initiatives in meeting the City's energy demands and its diversion from landfill. The dynamics of waste generation in Cape Town has been extensively researched and presented in Malla (2011), with some key findings drawn on here. Von Blottnitz (2006) stated that waste is landfilled at a rate of 2 kg per person per day in the Country's six metropolitan areas, which corresponds to 8.9 million tons of municipal solid waste (MSW) in 2005. Studies have indicated that up to 87% of the total waste generated in Cape Town is landfilled (Malla, 2011). In addition to this, the organic fraction of MSW contributes to approximately 40% of this waste stream (Greben *et al*, 2009).

City officials recognise the opportunity to recover energy from waste and as such, the City Council of Cape Town released an action plan in March 2011, *the Mayco resolution*, motivated by its commitments to the minimization of waste per its IWM Policy adopted in 2006, which is aligned with the national policy, *the White Paper on Integration Pollution and Waste Management for South Africa* (CoCT, 2011).

An assessment of alternative service delivery (ASD) opportunities for solid waste management in Cape Town identified the prospect for various Energy-from-Waste (EFW) initiatives and recommended the Solid Waste Management Department make use of public private partnerships (PPP) to add value to waste treatment, especially with energy recovery at City-owned sites such as their big transfer stations and selected landfill sites (CoCT, 2011).

The following section gives a brief description of the chemical structure of paper and identifies potential energy sources in the various waste paper streams.

2.2 Waste paper as an energy resource

2.2.1 The chemistry of paper

The chemical composition of paper is not fixed and is largely dependent on the source of the fibres used for its production. These fibres are essentially made up of cells of plants, the walls of which are comprised mostly of carbohydrate polymers (polysaccharides) impregnated with lignin. The most common of these is cellulose, a semi-crystalline structure (Figure 2-3), which occurs in microfibrils and is a linear polysaccharide of β-1,4-linked D-glucopyranose (Roberts, 2002).

These microfibrils are arranged in bundles within the cell wall which are then interlinked with hemi-cellulose and lignin. The plant cell wall is mainly comprised of cellulose (40-45%), followed by hemi-cellulose (13-35%) and lignin (17-35%), with the remainder (<10%) made up of extractives and trace organic compounds.

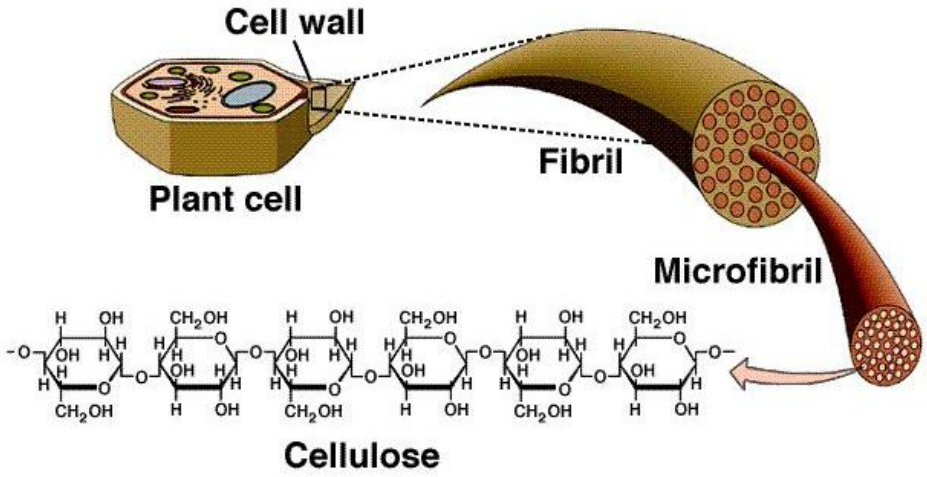


Figure 2-3: Molecular structure of the plant wall and cellulose (Roberts, 2002)

The chemical composition of paper is largely dependent on the feed material used and the chemical treatments and/ or mechanical pulping process it has been subjected to (Roberts, 2002). Higher grades of paper are composed of little or no recycled paper and thus consist of longer, stronger cellulose fibre strands. Processing during recycling breaks down these fibres, generating shorter strands and lower grades of paper.

This brings us to the various types of waste paper of interest, namely those that are destined for disposal (in landfill sites), either because they are non-recyclable, non-recovered or non-recoverable.

2.2.2 The status of waste paper management in South Africa and Cape Town

Analyses performed by the Paper Recycling Association of South Africa (PRASA) show that a total of 2.5Mt of paper was consumed in South Africa in 2010, of which office paper (36%) and corrugated materials (34%) make up the bulk of the total consumption, followed by newsprint (11%) and tissue (10%) (As depicted in Figure 2-4).

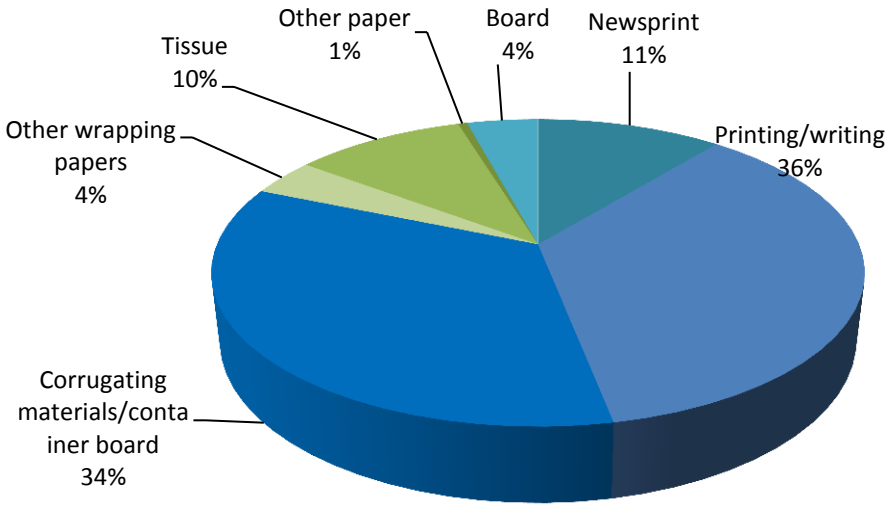


Figure 2-4: Paper consumption in South Africa (PRASA, 2010)

PRASA have categorized the recoverable papers into the following four grades:

	Description of paper grades	*Examples*
White, bleached grades	High quality, contains high grade cellulose Additional whitening through bleaching and addition of ash	Office and graphic paper for printing and scholastic purposes
Brown, unbleached grades	Manufactured from untreated, raw paper fibres	Corrugated board, kraft papers and solid containers
Mechanical grades	Either unprinted or printed, contain recycled paper	Newspapers and magazines
Mixed and other papers	These papers tend to be un-economic to sort and so are bunched together	Mixed recovered paper and board, mixed packaging, etc

2.2.2.1 Non-recoverable and non-recovered paper

Due to poor management these recoverable waste paper streams often bypass the recycling phase and are disposed of in landfill sites, where they may become contaminated and rendered unsuitable to be recovered for future reuse or recycling. Of the total paper products consumed, 75.6% is available for recovery, 8.4% is exported for the use in agricultural products and the remaining 16% is unsuitable for recovery (PRASA, 2010). The recoverable fraction of paper therefore corresponds to 1.9 Mt, based on the 2.5 Mt of overall paper consumption in South Africa in 2010. However, only 58% of this recoverable paper is successfully recovered for the purpose of reuse in the paper production sector; this corresponds to 1.1 Mt of paper products of the 1.9 Mt available, which means that a good 790 kilotons of paper products is either not recovered or sent straight to landfill.

In addition to the recoverable papers bypassing reuse due to poor waste management, the recycling market, particularly in Cape Town, periodically suffers saturation, releasing large quantities of reusable paper to landfill sites (Nissing and von Blottnitz, 2007), consequently decreasing the percentage of recovered waste paper being successfully utilized even further.

2.2.2.2 Non-recyclable paper

As reported by PRASA (2010), of the total paper products consumed, 16% is unsuitable for reuse. This portion comprises of sanitary papers and waxed papers. This corresponds to approximately 400,000 tons of paper in South Africa in 2010, and consists primarily of sanitary and waxed paper streams.

Sanitary paper: These are paper products used for sanitary purposes such as facial tissues, toilet paper, kitchen towels, and so forth; which consist of fully recycled paper and therefore have very short cellulose strands.

Waxed paper: Waxed paper is made from high grade cellulose, non-recycled paper and further coated with a wax layer (e.g. paper cups). Furthermore, the paper is given strength by blending with inorganic filler, which translates into a high ash content, making it unsuitable for reuse.

In addition to these non-recyclable paper streams, a large waste stream of **Recycled Paper Sludge (RPS)** is generated at recycling plants as there is a limit to the number of times paper can be recycled. This waste stream consists of short, non-recyclable cellulose fibres and generally has a high moisture content (~60%) as well. In Cape Town, a portion of these streams are thermally utilized at the paper factories, but the majority is sent to landfill (Nissing and von Blottnitz, 2007).

Based on the material and flow analysis (MFA) conducted by Nissing and von Blottnitz (2007), in Cape Town alone up to 139,000 tonnes of waste paper in various forms are sent to landfill sites annually and are thus potentially available for energy conversion. The following section provides an overview of waste to energy technologies.

2.3 An overview of Waste to Energy (WtE) technologies

Various studies have identified waste as a promising biomass source for both energy and other value added products. Figure 2-5 illustrates the energy technologies available for biomass conversion. Of these, three have been applied to waste-derived biomass and will be discussed further in subsequent sections.

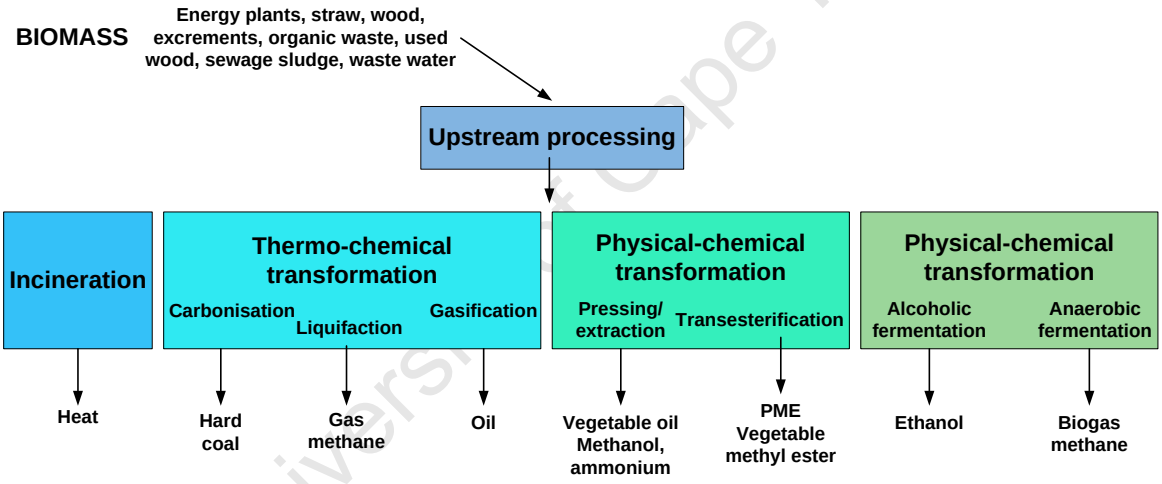


Figure 2-5: Energy conversion technologies for biomass (compiled using Deublein & Steinhauser, 2008)

These are the incineration, thermal and fermentation treatments. The former is carried out with excess air (incineration) to directly produce heat that can itself be used or converted to electricity; with limited air (gasification) to produce heat and fuel; or no air (pyrolysis) to produce fuel; whereas the latter are non-thermal and involve the use of microorganisms to convert the waste to fuel, either methane or ethanol.

2.3.1 Incineration

The incineration of waste is considered to be a mature technology, with up to 2,800 waste incineration facilities already well-established in Europe (AGAMA Energy Ltd, 2006). Incineration reduces the total volume of waste to 5 - 10% of the input, whilst sterilising hazardous components and simultaneously releasing thermal energy, which is recovered in the form of heat (hot water/steam). This heat can be converted to electricity or used as a combination of both electricity and heat.

Although incineration facilities have been well established in certain parts of the world, there still remain pressing environmental concerns surrounding the treatment of POPs, EDCs, slag, residues and dust emissions (AGAMA Energy Ltd, 2006). Some of these wastes can be reused, but others, such as dust, which makes up 7% (mass) of the total waste, can be problematic.

2.3.2 Other thermal conversion technologies

The study led by AGAMA Energy (Pty) Ltd (2006) provides an extensive discussion on both pyrolysis and gasification. ***Gasification*** results in some of the energy in the waste being recovered as a gas which can later be combusted in a boiler or gas turbine, with lower volumes of flue gas than that generated during incineration.

Pyrolysis, on the other hand, is a pre-treatment method which converts waste to a medium quality gas along with usable or treatable process residues. It is most frequently used as a stand-alone treatment, but can be followed by combustion of the gas or liquefaction (extraction of pyrolytic oil).

Both pyrolysis and gasification require high levels of control in terms of feed characteristics and composition, which is a problem in relation to waste, whose composition is dependent on social areas, seasons and change of consumer behaviour. For this reason both technologies have not gained much commercial success in comparison to incineration (AGAMA, 2006). The advantages to pyrolysis and

gasification, in comparison to incineration however, is the lowered overall emissions and the high energy conversion efficiencies of 30- 80%, depending on the energy conversion process used (efficiencies of up to 35% can be achieved for electricity generation).

2.3.3 Bio-methane production technologies

Methane can be used in a variety of stages of purity, generating few atmospheric pollutants and less carbon dioxide per unit energy than most other fuels. The conversion efficiencies of methane to electricity can range from 10% to 90% (ratio of electrical power to energy content of biogas feed) depending on the energy conversion technology efficiencies (Chynoweth *et al*, 2001). Biogas from anaerobic digestion ranges between 55% and 70% CH_4 on a volume basis and methane of a purity of 60% or more is suitable for use in the generation of heat or for that of electricity (Deublein and Steinhauser, 2008) therefore upgrading may be required.

The combustion of CH_4-rich stream in a gas turbine yields electrical efficiencies of up to 35%, whereas its use for the co-generation of both heat and power (CHP) has a global efficiency (η_{global}) of up to 90%. Electricity is generated as with the gas turbine at electrical efficiencies (η_{elec}) of up to 40%; the energy of the resulting hot flue gases is harnessed to generate useful heat resulting in a global efficiency (η_{therm}) of approximately 50% (Deublein and Steinhauser, 2008).

An alternative would be to clean the gas by separating the methane and carbon dioxide, and feeding it into the natural gas network. The CH_4 content must be at least 96%; and the removal of sulphur, lowering the oxygen and humidity levels is also necessary. Further cleaning and additional compression or liquefaction of the biogas allows for its use as a vehicle fuel. Four-stroke engines that have been adapted for natural gas are also suitable for this purpose (Deublein and Steinhauser, 2008).

2.3.3.1 Process Overview

Anaerobic digestion (AD) is the biological formation of methane that occurs naturally when organic material or biomass decomposes under humid atmospheric conditions in the absence of air, in the presence of a group of metabolically active micro-organisms (Deublien and Steinhauser, 2008). The AD process can be considered as four basic steps: hydrolysis or liquefaction, acidogenesis (fermentation), acetogenesis, and methanogenesis (Yunquin *et al*, 2009).

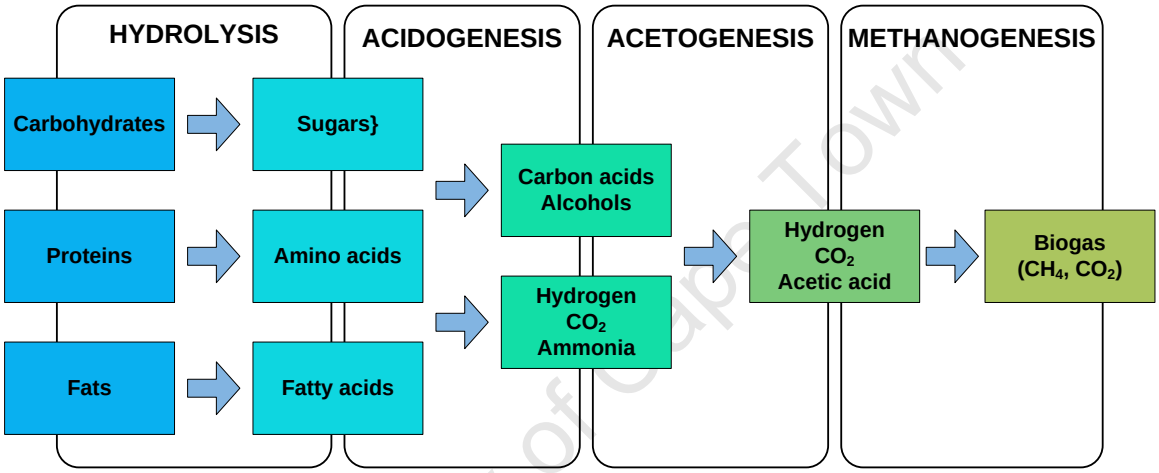


Figure 2-6: Process breakdown of anaerobic digestion

In the *hydrolysis* stage the insoluble carbohydrates (complex polymers) are broken down into soluble molecules. These soluble monomers are then fermented into short chain organic acids and alcohols during the *acidogenesis* stage as is depicted in Equation 2.1 and 2.2(Chynoweth *et al*.,1987).

$$Sugars \rightarrow CH_3CH_2COOH + 2H_2O \quad (2.1)$$

$$Amino\ acids \rightarrow Alcohols \mid Lactic\ acid \mid Fatty\ acids \quad (2.2)$$

During *acetogenesis* the alcohols are converted to acetic acid, carbon dioxide and hydrogen. In the *methanogenesis* stage the acetate is split into methane and carbon

dioxide (Equation 2.3) and hydrogen and carbon dioxide are also combined to produce methane (Equation 2.4) (Chynoweth *et al*.,1987).

$$CH_3CH_2COOH \rightarrow CH_4 + CO_2 \quad (2.3)$$

$$H_2 + CO_2 \rightarrow CH_4 + O_2 \quad (2.4)$$

Conventional anaerobic digestion has a high overall retention time of up to 60 days, of which 20-30 days are required for the hydrolysis of complex carbohydrates such as cellulose. Table 2-1 presents possible waste streams for anaerobic digestion, with an indication of their characterization and hazardousness.

There have been numerous successful large-scale biogas initiatives for both power generation as well as the implementation of biogas as vehicle fuel. An example of this is the local gas network in Switzerland, near lake Zurich, which is largely supplied by well-established biogas plants in the region. These biogas plants are powered by waste water from industries (food, animal feed and paper) and organic wastes from households, industry and agriculture (Deublein and Steinhauser, 2008). Similar projects such as these are well-established in both Sweden and Germany as well.

On the other hand, in a city in Sweden, as early as 1990, urban buses were refitted for the combustion of biogas and today an entire fleet, including taxis, private vehicles, refuse collectors and even the train, are driven by biogas (Deublein and Steinhauser, 2008).

Table 2-1: Characterization of possible waste streams for anaerobic digestion

	Examples of waste streams	*Description of substrate*
Residuals from beverage production	Mainly spent grains and fruits, used yeast, mash, etc	Harmless, little or no complexity
Animal waste	Meat and bone meal, blood, fats and stomach contents of slaughterhouse animals	Hygienised prior to digestion, may contain trash. Little to no complexity
Greens, grass, cereals, vegetable wastes	Garden wastes, leaves, straw, seeds, diverse cereals and various vegetable wastes such as peels	Harmless, little to high complexity
Waste from the food and fodder industry	Peels and pulp from vegetables and fruit, wheat wastes, oilseed residuals and molasses, etc	Harmless, may contain trash. Little complexity
Wastes from households and gastronomy	Bio waste, left over food, mixed fats and sewage and flotation sludge	Extensive treatment of bio waste due to contamination. Otherwise hygienised, high to little complexity
Wastes from pharmaceutical and other industries	Blood, egg and vegetable extraction residues, Paper industry waste, Pharmaceutical wastes	Hygienisation for contaminated wastes. Only paper waste is highly complex.
Productive livestock husbandry	Manure and excreta from cattle, pigs and chickens; also milk and starch wastes	All harmless; not complex

2.3.4 Bio-ethanol production technologies

In 2005, the worldwide production of ethanol was 45.6 x 10^5 m^3; more than 95% of which was of biogenic origin (Elvers, 2008). Approximately 80% of the ethanol produced is applied to the fuel sector; of which Brazil and USA are responsible for 90% of the fuel ethanol production (Figure 2-7).

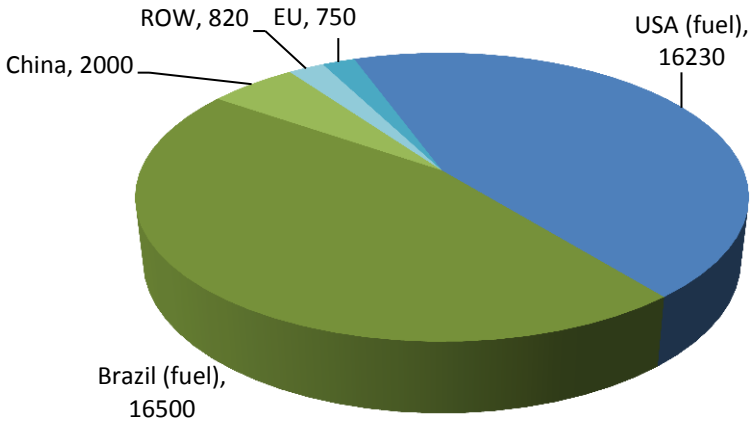


Figure 2-7: Worldwide ethanol production, 10^6 L (Deublein and Steninhauser, 2008)

Ethanol can be used as a partial gasoline replacement as in the U.S (E10, E15) and Brazil (E22).It is also directly blended with diesel or used as a "stand-alone fuel" (E85 and E100) as in Brazil (Sun and Cheng, 2001; Mielenz, 2001). Most car models in Brazil have a "flexi-fuelled" version, making up 50% of the current light vehicle fleets and 90% of current car sales. The U.S has followed suit with their plans to expand their numbers and variety of flexi-fuelled vehicles (Sun and Cheng, 2001). Ethanol can also be used as a hydrogen carrier for fuel-cell vehicles (Elvers, 2008).

Ethanol is predominantly used as a vehicle fuel or additive, however it can also be used in the conventional electricity generation technology, with slight modifications. The gas turbine converts up to 35% of its energy potential into electricity (η_{elec}). The large scale conversion of ethanol to power is a fairly new. In early 2010 Petrobas, Brazil's national energy company, launched an ethanol-fuelled power plant. The modified, dual gas turbines are able to run on either natural gas or ethanol.

2.3.4.1 Process Overview

Ethanol production from biomass essentially occurs in two stages. The first stage is the conversion of polysaccharides to monosaccharides through acid or enzymatic hydrolysis.

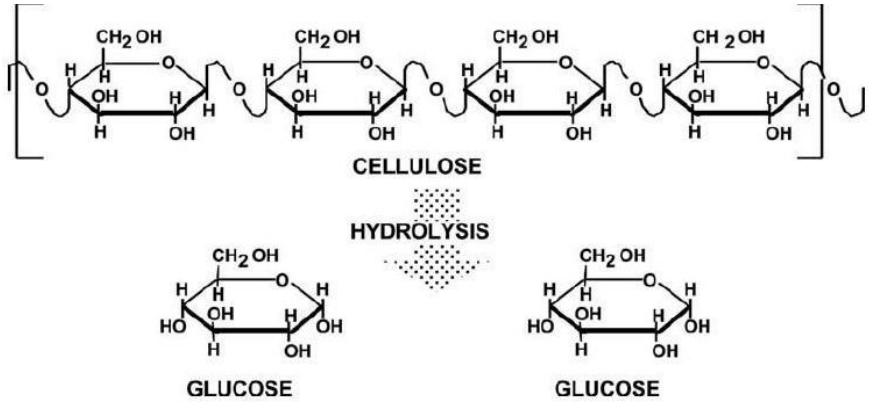


Figure 2-8: Hydrolysis of cellulose to glucose (Murphy *et al*, 2004)

The second stage is the conversion of the monosaccharides (glucose and xylose) into liquid ethanol via fermentation (Figure 2-9). Glucose forms two ethanol molecules and two CO_2 molecules, whereas xylose forms one ethanol molecule, one CO_2 molecule as well as water.

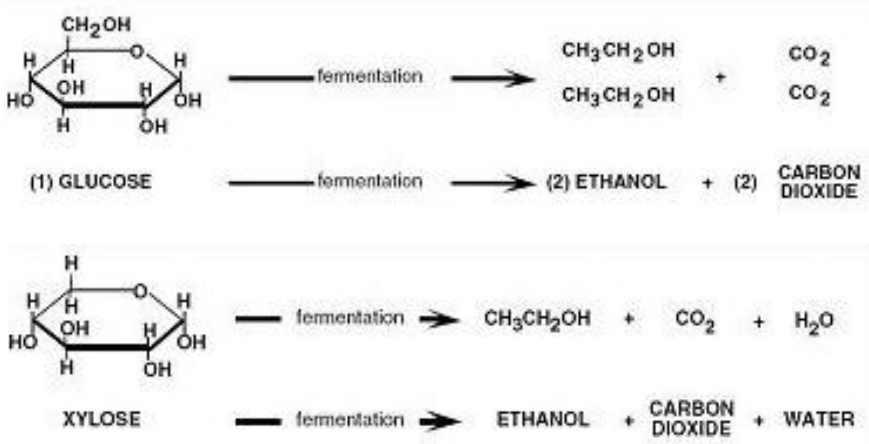


Figure 2-9: Glucose and xylose fermentation (Murphy, 2004)

Thus ethanol can be produced from any carbohydrate-containing material, the source of which may vary depending on the region of the world as well as the availability. The following table illustrates the dominant carbohydrates and example feedstock (Elvers, 2008).

Source	*Possible feedstock*
Starch	Cereals (corn, wheat, barley, sorghum/milo, etc), potatoes, casava
Sucrose	sugarcane and sugarbeet
Lactose	whey
Cellulose	wood and straw

There is a clear trend towards starch and sugar sources for ethanol production; however there has been considerable interest in cellulose-based feedstock due to the increased CO_2 emissions' savings associated with the process on an industrial scale among many reasons (Elvers, 2008). Wood-derived products, such as waste paper would therefore be an attractive choice as a possible feedstock bio-ethanol production. The following section summarises the literature related to waste paper conversion to bio-ethanol.

2.4 Review of bio-ethanol systems involving waste paper

Incineration is often the alternative method of disposal for waste paper streams, but due to the high moisture content large costs are sometimes incurred for this approach (Marques *et al*, 2007). In the case of recycled paper sludge (RPS), which contains up to 63% water, bio-ethanol conversion is often proposed as a very attractive option.

Studies involving the conversion of waste paper to bio-methane were fairly limited, whereas extensive work has been done involving the conversion of waste paper sources to bio-ethanol. The following studies involving bio-ethanol production were therefore selected based on the limitations of the biogas-based studies so as to fairly compare the yields obtained.

Both Lark *et al* (1997) and Marques *et al* (2007) studied RPS as a feedstock for bio-ethanol production. Liu *et al* (2008) looked at a sample of mixed waste paper (MWP) provided by CTA-TEX Chemical Co. Ltd. in China whereas Kadar et al (2003) looked at RPS and old corrugated cardboard (OCC). Detailed tables of the compositions are attached in the Appendix. The following table describes the operating conditions for the various feedstock used, followed by the corresponding ethanol yields (Table 2-2).

Table 2-2: Experimental setups for previous studies using waste paper for ethanol production

	Lark et al (1997)	*Marques et al (2007)*	*Kadar et al (2003)*	*Liu et al (2008)*
Feedstock	RPS	RPS	RPS and OCC	MWP
Temperature (°C)	38	30	40	43.1
pH buffer at start of experiment	Potassium phosphate (pH=5)	Sodium citrate (pH=5.5)	N/A	Citrate (pH=4.5)
pH control	None	None	NaOH or H_2SO_4 (pH=4.4-5.3)	None
Duration (h)	72	48	72	72
Process	SSF	SSF	SSF	Fed-batch SSF
Enzyme	*Trichoderma* cellulase	Celluclast	Celluclast 1.51/ logen Cellulase	Cellulase ZC-1700
Yeast/bacteria	*K. Marxianus* ATCC 36907	*Pichia stipitis CBS 5773*	*K. Marxianus* Y01070/ *S.cerevisiae*	*K. Marxianus* DW08

Table 2-3: Bio-ethanol yields obtained for selected waste papers

		Lark et al (1997)	*Kadar et al (2003)*		*Liu et al (2008)*
Feedstock		RPS	RPS	OCC	MWP
Ethanol yield	kg EtOH/ kg dry substrate	0.184	-	-	0.287
	kg EtOH/ kg cellulose	-	0.33	0.312	-

The following sub-sections discuss the various process options for improved bio-ethanol yield, including: simultaneous or sequential hydrolysis and fermentation, enzymes for hydrolysis, process configuration choice, and yeast or bacteria selection.

2.4.1 SSF versus SHF Process

Various studies have been performed to determine whether it would be better to carry out the hydrolysis and fermentation sequentially (SHF) or simultaneously (SSF). In one such study (Marques *et al,* 2007), the ethanol volumetric production rate and total residence time favoured the SSF process, however, the extent of conversion was higher for SHF process than that for the SSF process. They contribute this to the different process temperatures (30°C for the SSF process and 35°C for the hydrolysis of the SHF process, which naturally corresponds to a higher enzyme activity). These results were based on the assumed theoretical yield of 0.51g ethanol/g glucose.

Typically studies performed SSF using native lignocellulosic feedstock. It was found that a cost associated with the cellulase enzyme was the largest contributor to the total cost (Lark *et al*, 1996). Other than the inhibitory effects of the lignin, native lignocellulosic feedstock also requires size reduction for both hydrolysis and fermentation to be effective. In the case of waste paper, in particular RPS, due to its extensive treatment further size reduction is not required and the lignin content is significantly reduced as well. Cellulase use would thus be less, which would therefore considerably lower overall costs (Lark *et al*, 1996; Marques *et al,* 2007).

2.4.2 Enzymes for hydrolysis

Enzymatic hydrolysis is preferred as opposed to the conventional method of acid hydrolysis as the enzymes are more specific and the process is generally cleaner, it also allows for milder operating conditions and the "catalyst" is potentially re-usable (Marques *et al*, 2007). Enzymatic hydrolysis of cellulose is typically carried out at 50°C using cellulase, which is produced by the aerobic fungi *Trichoderma ressei*. This enzyme is essentially a complex of endo-β-1,4-glucanase, exo-β-1,4-cellobiohydrolase, and glycosidase. These enzymes act together in a synergistic manner as each has a different property in the hydrolysis of cellulose (Shen, J., 2008).

2.4.3 Batch versus fed-batch reactor

Ballestaros *et al* (2002) found that high enzyme loading and low substrate concentrations gave the best ethanol yields for SSF at standard conditions (batch process). Ideally, we want high substrate concentrations for high ethanol concentration with lower enzyme loading. An increase of substrate concentration, however, causes mixing difficulties, ultimately resulting in lower ethanol yields.

The fed-batch approach involved the addition of 5, 3 and 2% (w/v) substrate loading at 24h intervals as opposed to a substrate loading of 10% (w/v) for standard SSF batch process. This allows for partial saccharification, and thus a more fluidised mixture for more substrate to be added. The results indicated an increase in ethanol yield from 56.4% to 79.7% using the fed-batch approach. This correlates with the higher ethanol yields achieved by fed-batch studies (Liu *et al*, 2008) than other standard SSF studies (Kadar *et al*, 2003).

2.4.4 Yeast/ bacteria for fermentation

Many types of yeast and some bacteria can convert glucose to ethanol, the genus *Saccharomyces* being the most common. However, yeasts have some significant limitations as they have low substrate range and limited tolerance of ethanol (Shen, J., 2008). Another issue is that associated with the SSF process. The hydrolysis and fermentation steps have different optimal temperatures, namely 50°C for enzymatic

hydrolysis using cellulose and 30°C for fermentation using the traditional *saccharomyces* yeast strains. Previous studies have shown that *Kluveromyces, Saccharomyces* and *Candida* strains are all able to ferment sugars above 40°C, but *Kluveromyces* is more thermotolerant than the latter two.

Kadar *et al* (2003), however, evaluated both *K.Marxainus* and *S.Cerevisiae* for SSF at 40°C, indicating no significant difference between their performances. Further studies indicate that *Kluveromyces* strains achieve the best conversions at 42°C, in particular, *K.Marxianus* Y01070. It would be safe to say then that, based on these results, the generally used *S.Cerevisiae* can be used at 40°C in the SSF process, but a *K.Marxianus* strain should be used in the case of temperatures between 40 and 45°C.

2.5 Review of bio-methane systems involving waste paper

In a study by Gunaseelan *et al* (1997) various fractions of municipal solid waste (MSW) were anaerobically digested to determine its potential for methane production. In particular, the bio-chemical methane potential (BMP) of a series of paper fractions were determined (see Appendix9.1). These were characterised based on the volatile solids, or VS, content (organic matter as ash-free dry weight) and the percentage of poorly biodegradable materials. A methane yield, or BMP, based on this VS content was determined for the digestion of waste paper under mesophilic (35°C) conditions (Figure 2-10).

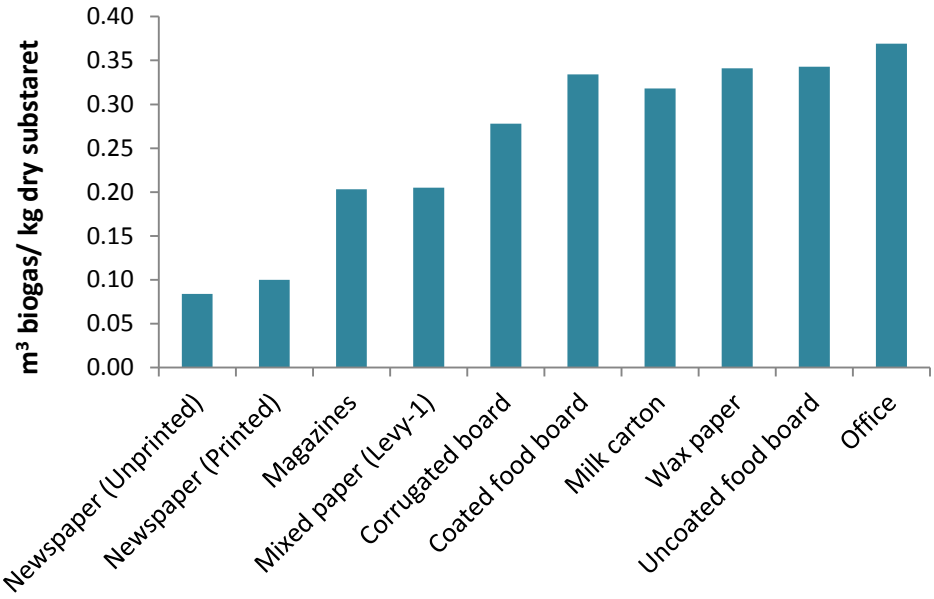


Figure 2-10: Bio-chemical methane potential (BMP) of various paper samples in m^3/kg dry substrate (compiled using *Gunaseelan, 1997)*

As was discussed in Section 2.2.2 the composition and properties of various paper types differ due to the mechanical and chemical treatments they are subjected to. It is no surprise then that the highly refined mechanical grades, newspaper and magazines, resulted in the lowest methane yields. Similarly, the office paper, which is of a very high quality and contains mostly virgin feed, resulted in the highest methane yield.

As indicated in section 2.3.3, the disadvantage of substrates containing complex carbohydrates, such as paper, is the lengthy retention times. There are various approaches to overcoming this setback such as alternative process configurations, disintegration of feedstock and different process conditions with the implementation of substitute bacteria. Substrate selection is also of great importance. The following sections address these topics.

2.5.1 Process conditions

Most full-scale plants treating solid waste residues with anaerobic digestion are operated at mesophilic temperatures (35 - 38°C). It has been successfully demonstrated that the organic fraction of MSW (OF-MSW) can be treated at thermophilic conditions (55°C), resulting in higher loading rate capacity and increased biogas production volumes due to enhanced hydrolysis and improved organic solids destruction (Angelidaki *et al*, 2006).

The difficulties associated with control and process stability around start-up of the process can be overcome with the use of low fresh TS (total solids ~1.5%); addition of at least 10-15% of final inoculum volume at start-up and intermittent addition and progressive increase of substrate (Angelidaki *et al*, 2006).

2.5.2 Process configurations

The acid- and methane-forming phases are usually performed simultaneously in a single stirred-reactor system, CSTR or preferably (intermittently) fed-batch. This requires a balanced environment for the microorganisms as they differ in terms of their physiology, nutritional needs, growth kinetics and sensitivity to other environmental conditions (Demirel and Yenigun, 2002). Two separate reactors can be implemented to accommodate the unique requirements for each of the acid- and methane-forming phases.

The total digestion time was found to be considerably lower for the two-phase digestion, but showed no difference in the biogas yields. Gunaseelan *et al* (1997) proposed the capture of hydrogen in the first phase and recycle to the second phase to increase the overall biogas yield.

2.5.3 Disintegration

Although cellulosic substrates are much cheaper than starch-based raw materials, they can be more difficult to biodegrade making disintegration an attractive option to attain a more efficient, cost effective system. Disintegration is essentially the breakdown of the organic cells to allow the products to ferment more easily. An extensive list of process technologies is given in Deublein and Steinhauser (2008). Some common examples are mechanical technologies such as an agitator ball mill, to chemical technologies such as acid-/ alkali treatment, and biological process technologies such as enzymatic treatment.

As mentioned prior to this section, the hydrolysis phase of biogas production accounts for ~20 days of the total 45 - 60 days necessary for biogas production. The implementation of the disintegration can be applied at different stages of the process, after which maximum hydrolysis yields may be obtained after only 3 to 4 days.

2.5.4 Co-digestion

The ideal or acceptable carbon to nitrogen (C:N) ratio for sufficient AD to occur is 20:1 – 30:1. Paper-derived biomass sources, however, generally have a high C/N ratio in the range of 173:1 to that greater than 1000:1 and thus co-digestion with a suitable nitrogen source has been considered. It was shown that co-digestion of algal sludge and waste paper has a significant effect on the production of methane, with an optimal ratio of 20:1-25:1 (Gunaseelan, 2006; Yen *et al*, 2007) as well as improved production rates during anaerobic digestion (Siddiqui *et al*, 2011).

All in all, anaerobic digestion using wet feedstock does have various advantages over other waste to energy technologies, such as the (i) low installation and operational costs, (ii) standard operating conditions, and (iii) low maintenance (AGAMA Energy Ltd, 2006), as well as (iv) low product separation costs (Chynoweth *et al*, 2001).

2.6 Potential bio-energy yields for a selection of waste paper types

A comparison between the bio-ethanol and the bio-methane options for energy recovery from waste paper is complicated by the different reporting bases used in these two fields. This section aims to present such a comparison in equal units. Based on the data obtained from literature and presented above, the expected energy yields for both ethanol and biogas production were calculated for three specific streams of waste paper, namely: recycled paper sludge (RPS), mixed waste paper (MWP) and old corrugated cardboard (OCC).

Research into the conversion of RPS to ethanol is fairly broad (Lark *et al*, 1997; Marques *et al*, 2007; Kadar *et al*, 2004); however studies involving RPS conversion into biogas were unavailable. The various paper fractions of the mixed waste paper stream used in Liu *et al* (2008) was not given, but should contain any kind of clean waste paper and cardboard that is not a magazine, newspaper or corrugated cardboard. However, it should be noted that the sample assessed for the biogas production (Gunaseelan, 1997) contained 7 wt. % corrugated cardboard and 85 wt. % unspecified paper.

A basis of 1kg VS of untreated feedstock was used for the calculations. The ethanol and biogas produced were calculated using the reported conversion yields depicted in

Table 2-3 and Table 2-4 below, the latter of which was compiled using Figure 2-10. Where the yields were specified per kg cellulose it was assumed that the VS consisted solely of cellulose and the remainder was ash with zero calorific value.

Table 2-4: Bio-methane yields [m^3 CH_4/ kg VS] for selection of waste papers

Feedstock	
OCC*	MWP*
0.205	0.278

The *lower heating values* (LHV) for ethanol and methane, 26.7 MJ/kg EtOH and 34.6 MJ/m^3 CH_4 respectively, were then used to determine the resulting energy yields (see Appendix 9.1) displayed in the figure below. The LHV is the energy (MJ) obtained through the combustion of 1 kg (dry mass) of a particular material. The LHV was used here as the substrates dealt with were on a dry mass basis as opposed to using the *higher heating value* (HHV) which includes the energy required to evaporate the water in 1 kg of a moist substrate.

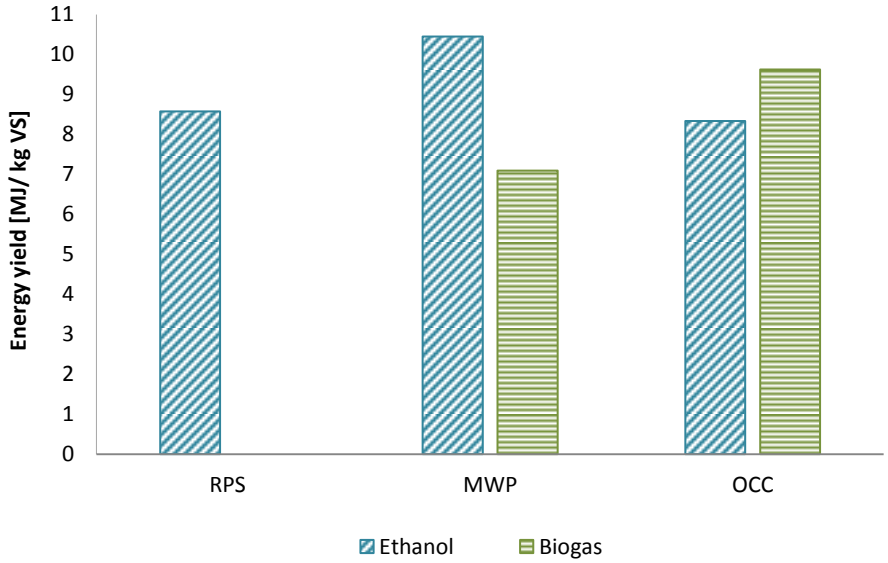


Figure 2-11: A comparison of biogas and bio-ethanol energy yields [MJ/kg VS_{FED}] produced from various waste papers

It was assumed, when not specified, that the VS translates into the cellulose content. Due to the differentiation in the composition of the dry mass of the various substrates, a more fair comparison was able to be performed in this way. The lower heating value of 16 MJ/ kg cellulose was used to calculate the fraction of the LHV that was recovered into either ethanol or biogas (see Appendix 9.1).

Table 2-5: Percentage of LHV recovered into biogas and bio-ethanol

	Bio-thanol production	*Biogas production*
RPS	52 - 55 %	NR
MWP	65%	44%
OCC	52%	60%

Overall, the two technologies appear to produce similar energy yields: Bio-ethanol conversion technologies produce a higher energy yield for MWP, with an LHV recovery of up to ~65% for the MWP, whereas the anaerobic digestion produces a higher yield and an LHV recovery of 60% for OCC (Figure 2-11).

Based on these preliminary calculations, the LHV recovery into bio-energy overall is quite significant for both ethanol and biogas technologies, varying with the type of paper feedstock. Further tests will need to be done to assess the effects of using other waste paper streams that have not been considered thus far, such as using RPS for biogas production.

These energy yields only take into consideration the production process itself and not the subsequent separation process, in the case of the ethanol production, as well as end use efficiencies. For a more meaningful comparison of the technologies, it is therefore necessary to perform an analysis over both the bio-energy conversion process itself, including the subsequent processes thereafter to obtain overall energy yields, and over the full energy product life cycle, to account for different end-use efficiencies and pollutant emissions.

2.7 Recent Life Cycle Assessments on WtE (BEfW) Systems

Life Cycle Assessment (LCA) studies involving biomass to energy in the form of both transport fuel as well as power generation have been quite extensive in recent years, including those involving energy from waste-derived biomass. This section of the study reviews the current state of the art knowledge in waste-to-energy practices.

2.7.1 Life Cycle Assessment methodology

The technique of Life Cycle Assessment (LCA) was developed as a result of an increased awareness in environmental protection and a desire to better comprehend and reduce the possible impacts associated with goods manufactured and consumed using a holistic approach. For a *cradle-to-grave* assessment one needs to consider both upstream and downstream inputs and outputs, from raw materials acquisition right through to the use and final disposal of the product or service.

The detail and timeline of an LCA is dependent on the definition of the goal and scope of the assessment. This includes the objectives and the desired application thereof, which will in turn indicate the type of LCA to be implemented. There are essentially two main types of LCA; the *consequential* LCA describes a modelling procedure which seeks to identify the environmental consequences of a decision or a proposed change in a system under study (Weidema *et al*, 2009). *Attributional* LCAs, on the other hand, seeks to establish the burdens associated with the production and use of a product, or with a specific service or process, at a point in time (Finnveden *et al*, 2009).

The focus of the consequential and attributional LCAs differ in several methodological choices, one of which is the use of *average* or *marginal* data in the modelling of the subsystems of the life cycle. The former represents the average environmental burdens for producing a unit of the good and/or service in the system; whereas the latter represents the effects of a small change in the output of goods and/or services from a system on the environmental burdens of the system (Finnveden *et al*, 2009). Attributional LCA excludes the use of marginal data, while consequential LCAs use

marginal data when relevant for the purpose of assessing the consequences (Finnveden *et al*, 2009).

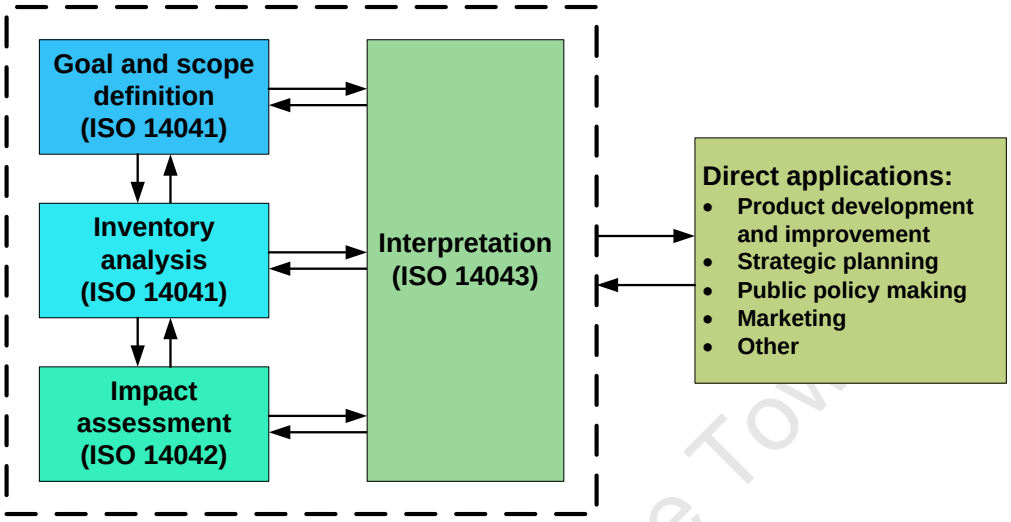


Figure 2-12: Phases and application of an LCA (based on ISO 14040) sourced from Varun *et al* (2008)

A life cycle assessment has four integrated phases (Figure 2-12). Once the goal and scope has successfully been defined, an inventory is compiled consisting of all the inputs and outputs of the product system, the potential environmental impacts associated with these inputs and outputs are evaluated and finally these results are interpreted in relation to the objectives of the study. An LCA can assist in (ISO14040):

- Identifying opportunities to improve the environmental aspects of products at various points in their life cycle;
- Decision-making in industry, governmental or non-governmental organizations (e.g. strategic planning, priority setting, product or process design or redesign);
- Selection of relevant indicators of environmental performance, including measurement techniques; and
- Marketing (e.g. an environmental claim, eco-labelling schemes or environmental product declaration)

In recent years, there have been many studies implementing the LCA technique to evaluate the environmental and technical merits of biofuels from various waste sources. Its holistic and systematic approach assists in making a rational assessment of bio-energy systems.

2.7.2 Overview of published studies involving BEfW systems

2.7.2.1 Bio-ethanol systems

A review was conducted of various assessments involving bio-ethanol as a transportation fuel from both farmed feedstock and waste feedstock (von Blottnitz and Curran, 2007), the latter being of interest. This group included: maize (or "corn") stover, wheat straw, ligno-cellulosic materials generally (wood, straw, crop residue), and sugarcane processing residues (molasses and bagasse). Of the studies that were reviewed, much of the focus was on whether or not the conversion of the waste biomass to biofuels provides a net energy gain or loss with respect to the energy input versus the energy provided by the biofuel. The overriding conclusion was that the production of bio-ethanol as a replacement for conventional fuel or as an additive did in fact result in a net energy gain; with the dominating factors of energy performance being crop or climate productivity and the nature of the feedstock (von Blottnitz and Curran, 2007).

For those studies that involved environmental impacts, it was found that bio-ethanol results in reductions in *resource use* and *global warming*. The harvesting and processing of the biomass is responsible for unfavourable impacts on acidification, human toxicity and ecological toxicity.

In a later study conducted by Melamu and von Blottnitz (2009), a comparison was made between carbohydrate-derived bio-ethanol and hydrogen for transport and electricity application on the basis of environmental performance. A Life Cycle Assessment (LCA) approach was adopted, comparing these energy products within the coal-intensive economy of South Africa. The results indicated that, for bio-ethanol, the electricity

options performed significantly better in all the impact categories selected with the exception of the *Global Warming Potential* (GWP), which displayed a marginal difference. In addition to the GWP, the following impact categories were considered: human toxicity, acidification and fresh water aquatic toxicity. The study accounted this result to the nature of the replaced electricity; which in the South African case has higher emissions of SO_X, NO_X and particulates per kWh of electricity produced than that of a set of 16 European countries (von Blottnitz, 2006). The following section reviews a selection of LCA research involving bio-methane from waste sources.

2.7.2.2 Bio-methane systems

The following table presents LCAs of bio-methane systems that are relevant to this study and it is characterised with respect to location, source of waste feedstock and the scope of the evaluation (Table 2-6). The LCAs presented here were selected based on the feedstock, namely cellulosic waste residues or MSW containing paper fraction. In addition to this the LCAs reviewed were holistic and addressed multiple environmental impacts and/or energy analyses.

Table 2-6: Description of various LCA (Full) studies involving waste to biogas systems (from 2004 onwards)

Study	*Waste feedstock*	*Location*	*Scope of evaluation*
Murphy and McKeogh (2004)	Municipal solid waste (MSW)	Ireland	Net energy analysis, GHG savings, economic analysis
Chevalier and Meunier (2004)	Crop residues (unspecified)	Austria	Resource depletion, climate change, Acid., Eutrophication (Eco-indicator 99), DALY, PDF
Berglund and Borjesson (2006a and 2006b)	Manure (cow, pig), OF-MSW, slaughterhouse waste, tops and leaves of sugar beet, straw, grease separator sludge	Sweden	Energy performance (input/output ratio), fuel-cycle emissions
Chaya and Gheewala (2006)	Municipal solid waste (MSW)	Thailand	All Eco-indicator 95 impact categories
Cherubini and Ulgiati (2009)	Crop residues (corn stover and wheat straw)	U.S	All CML 2 Baseline 2000 impact categories, GHG balance, energy balance
Kiatkittipong et al (2009)	Crop residues (bagasse)	Thailand	GWP, Acid., Eutrophication,PO (EDIP/UMIP 97)

Berglund and Borjesson looked at the energy performance of the life-cycle of biogas production from various raw materials (2006a) and the fuel-cycle emissions of its use in boilers for heat, CHP, transportation fuel in light- and heavy-vehicles (2006b). It was found that the net energy output was material specific, where raw materials with high water content and low energy yield that require extensive handling increases the energy input. The primary energy input corresponds to approximately 20% to 40% of the energy content of the biogas produced; with 40% to 80% of the primary energy input demands used for operation of the biogas plant (Berglund and Borjesson, 2006a).

With regards to fuel-cycle emissions it was found that this could vary extensively depending on the biogas system studied, however key factors are the choice of the raw material, energy efficiency of the biogas production plant and the status of the end-use technology. Extensive handling of raw materials is a source of significant emissions. The emissions associated with the production phase far exceed that of the end-use phase.

In comparison to various fossil reference systems (Chevalier and Meunier, 2004; Cherubini and Ulgiati, 2009; Murphy and McKeogh, 2004) biogas systems show improvements with respect to global warming effects and reduce fossil energy demands. The extent of the GHG savings are however dependent on the fossil reference systems.

Other studies investigated the use of biogas from waste for the use in electricity generation, for combined heat and power (CHP) production or as a transport fuel, in comparison to "do-nothing" scenarios involving landfilling (Kiatkittitipong *et al*, 2009; Chaya and Gheewala, 2006; Murphy and McKeogh, 2004). Potential impacts would be avoided due to net electricity production (global warming, acidification, stratospheric ozone depletion, photo-oxidant formation) as well as an improved net energy reduction and reductions in fossil resource demands compared to that of thermal technologies, such as incineration and gasification.

With respect to greenhouse gas savings (tons CO_2 per annum) Murphy and McKeogh (2004) illustrated that the biogas-based electricity options displayed greater savings than that for transport fuel for all "do-nothing" scenarios considered. These scenarios involved landfilling of the waste and either flaring or no flaring of the landfill gas. In addition to this, it was shown that combined heat and power use of produced biogas is always better than electricity generation alone, with respect to the annual CO_2 savings (Murphy and McKeogh, 2004).

2.7.2.3 Comparing different bio-fuels for different end-use applications

Allocation procedures are required when dealing with systems involving multiple outputs or when comparing systems with differing functional outputs; such as wattage in the case of electricity options and mileage for the transport fuel options. The option recommended by the ISO standards is to expand the system boundary of the studied systems to include alternative ways to provide the additional functions so that all the scenarios yield comparable product outputs.

System expansion was used in the study of Melamu and von Blottnitz (2009) involving the analysis of the projected environmental performance of two maize-derived energy products, ethanol and hydrogen. The end-use applications considered for both ethanol and hydrogen systems were electricity and transport fuel, two directly incomparable services. System expansion was therefore implemented through the addition of the conventional coal or oil-based methods of producing electricity and transport fuel so as to deliver an extended *system functionality* which includes an overall electricity capacity and achieved mileage (Melamu and von Blottnitz, 2009) for a specific reference flow.

2.8 Summary

This chapter has provided a review of the national and city context, as well as an organisation and analysis of the literature relevant to this study. This closing section summarises the core findings in relation to the key questions put forward in Chapter 1.

I. ***What energy yields can be achieved for bio-methanation and for hydrolysis-fermentation to fuel bio-ethanol of wet, uncontaminated non-recyclable paper?***

The following table provides a summary of the energy yields obtained for specific waste papers, as drawn from published studies. The yield was calculated on a basis of 1 kg volatile solids (VS) using the yields reported in literature. As the yields were generally reported per kg cellulose for the ethanol options, it was assumed that the VS consisted solely of cellulose. An LHV of 26.7 MJ/kg EtOH and 34.6 MJ/m^3 $CH_4$was used for ethanol and methane, respectively, and so the bio-methane and bio-ethanol energy yields could be compared.

Table 2-7: Summary of reported bio-ethanol and bio-methane yields for a selection of waste papers [MJ inherent energy/ kg VS]

	Bio-ethanol Production	*Biogas production*
RPS	8.34 - 8.80	NR
MWP	10.45	7.09
OCC	8.33	9.62

The results in Table 2-7 were earlier reported as percentage yields in subsection 0. The percentage recovery for both bio-methane and bio-ethanol was substantial, with a maximum energy yield and recovery obtained for bio-ethanol from MWP. However, the MWP displayed the lowest energy yield and percentage recovery for bio-methane production. There were no studies involving RPS to bio-methane, however those involving conversion to bio-ethanol were fairly extensive.

II. *What are the efficiencies of bio-ethanol and bio-methane conversion to power generation?*

The following table summarises the efficiencies of the electricity generation technologies suitable for the bio-energies in question which was discussed in subsections 2.3.3 and 0. Bio-ethanol can easily be used in its liquid form in a conventional gas turbine with an electrical efficiency of 35% (Table 2-8).

Table 2-8: Summary of efficiencies of selected electricity generation technologies

	Electrical efficiency (η_{ELEC})	Global efficiency (η_{THERM})
Gas turbine	~35 %	-
CHP	30 - 40 %	80 - 90 %

Methane of a purity of 60% or more is suitable for use in the generation of heat or for that of electricity (Deublein and Steinhauser, 2008). Anaerobic digestion yields biogas of a CH_4 content ranging from 55 – 70%, thus after some treatment it can either be used in a gas turbine with 35% electrical efficiency or for the co-generation of both heat and power (CHP). An electrical efficiency of up to 40% can be achieved; with an overall efficiency of up to 90% (Deublein and Steinhauser, 2008).

III. *What factors, other than energy yield, should be considered in developing a preference?*

A selection of relevant studies involving the assessment of bio-ethanol or bio-methane from waste systems was reviewed. There have been no LCA studies addressing the conversion of bio-ethanol from waste paper streams, such as recycled paper sludge. The focus of the majority of the bio-ethanol studies were on the technical merits of mostly crop bio-ethanol, particularly on whether or not the system yielded a net energy gain or not. The following overriding conclusions were identified:

- In a review of various studies involving the production of bio-ethanol as a replacement for conventional fuel or as an additive from both farmed and waste feedstock (von Blottnitz and Curran, 2007), the results indicated a *net energy gain* was achieved; with the dominating factors of energy performance being crop or climate productivity and the nature of the feedstock.

- With respect to the environmental performance, it was found that bio-ethanol production results in *reductions in resource use* and *global warming*; however the harvesting and processing of the biomass is responsible for *unfavourable impacts* on *acidification*, *human toxicity* and *ecological toxicity* (von Blottnitz and Curran, 2007). In this regard, waste-derived feedstock should present an attractive option in improvements in environmental performance.

- In a study comparing the environmental merits of bio-ethanol and hydrogen for electricity generation and transport fuel (Melamu *et al*, 2009), it was found that bio-ethanol for electricity generation performed significantly better than bio-ethanol as a transport fuel with respect to *human toxicity*, *acidification* and *fresh water aquatic toxicity*, with the exception of the *Global Warming Potential* (GWP), which displayed a marginal difference.

The major findings associated with the bio-methane systems involving waste systems were as follows:

- The primary energy input and emissions associated with the production phase far exceed that of the end-use phase, where the extensive handling of raw materials is a large source of emissions (Berglund and Borjesson, 2006b). Approximately 40% to 80% of the primary energy input demands is used for operation of the biogas plant (Berglund and Borjesson, 2006a).

- Murphy and McKeogh (2004) illustrated that the biogas-based electricity options displayed greater greenhouse gas savings (tons CO_2 per annum) than that for transport fuel for “do-nothing” scenarios involving landfilling of the waste and either flaring or no flaring of the landfill gas.

- Biogas for combined heat and power is always better than electricity generation alone, with respect to the annual CO_2 savings (Murphy and McKeogh, 2004).

IV. How does contamination affect performance and preference?

Paper is predominantly made up of cellulose, with slight variations depending on the grade. This cellulose content translates into a high carbon to nitrogen ratio (C:N), ranging from the range of 173:1 to that greater than 1000:1. The ideal or acceptable C:N ratio for sufficient anaerobic digestion to occur is 20:1 – 30:1.

As such, the addition of a nitrogen-rich substrate to adjust the C:N ratio of waste papers presented a marked improvement in a selection of studies. The co-digestion of algal sludge and waste paper demonstrated a significant improvement of the methane production yields; performing optimally at a ratio of 20:1 - 25:1 (Gunaseelan, 2006; Yen *et al*, 2007). Similarly, co-digestion of carbon-rich paper waste with substrate rich in nitrogen displayed enhanced production rates as well (Siddiqui *et al*, 2011).In that regard, anaerobic digestion would be an attractive option for the contaminated fraction of the waste paper streams.

3 APPROACH AND METHODOLOGY

This chapter starts by developing two hypotheses, building on the literature review and the objectives for the study as laid out in Chapter 1 and 2. It then proceeds to describe the methodology adopted to test the hypotheses and so to build onto the partial answers to the key questions put forward at the end of the literature review.

3.1 Hypotheses

It is the aim of the research to substantiate the following hypotheses:

Hypothesis 1: Relatively uncontaminated forms of non-recyclable paper will become an attractive feedstock for commercial fuel bio-ethanol production, especially where flex-fuel vehicles are wide-spread – however, this will not represent the most energy-efficient or environmentally friendly energetic usage of this type of waste paper.

Essentially what this means is that, although uncontaminated forms of non-recyclable paper would be an attractive option for fuel-ethanol production, other alternatives to the energetic use of waste paper would be more environmentally friendly or energy efficient for that matter. Here ethanol- and biogas-based electricity options are considered as such alternatives.

Hypothesis 2: Forms of non-recyclable and non-recoverable paper which are more contaminated will co-digest well in anaerobic digesters set up to recover energy from waste and reduce volumes for disposal, boosting gas yields per unit of digester volume, especially when used to adjust carbon to nitrogen ratios.

The second hypothesis is focused on the biogas-based electricity options only, postulating that the co-digestion of carbon-rich waste paper with nitrogen-rich substrates would boost gas yields per unit digester as well as reduce volumes for disposal.

3.2 Overview of the procedure

The overall procedure used to test the hypotheses put forward was twofold; the first of which is a laboratory experimental approach as depicted in Figure 3-1 below, designed to produce Bio-Chemical Methane Potential (BMP) estimates for waste paper sludge that were identified to be missing in the literature, and needed to address *Hypothesis 1*. The BMP is essentially the bio-methane yield per unit of digestible material (further detailed in Section 4.

Contamination was not itself investigated here, but a co-digestion with a protein-containing substrate was used as a proxy for the presence of other potentially trouble-some substances. Extending the experimental work to co-digestion scenarios with nitrogen-rich substrates also allowed addressing *Hypothesis 2*. Based on the objectives and performance criteria, an experimental design was developed that involved bio-chemical methane potential (BMP) assays of the carbon-rich WPS and a selection of nitrogen-rich substrates. A detailed description of the materials and methods used is presented in Chapter 4, followed by the results and discussion thereof in Chapter 5.

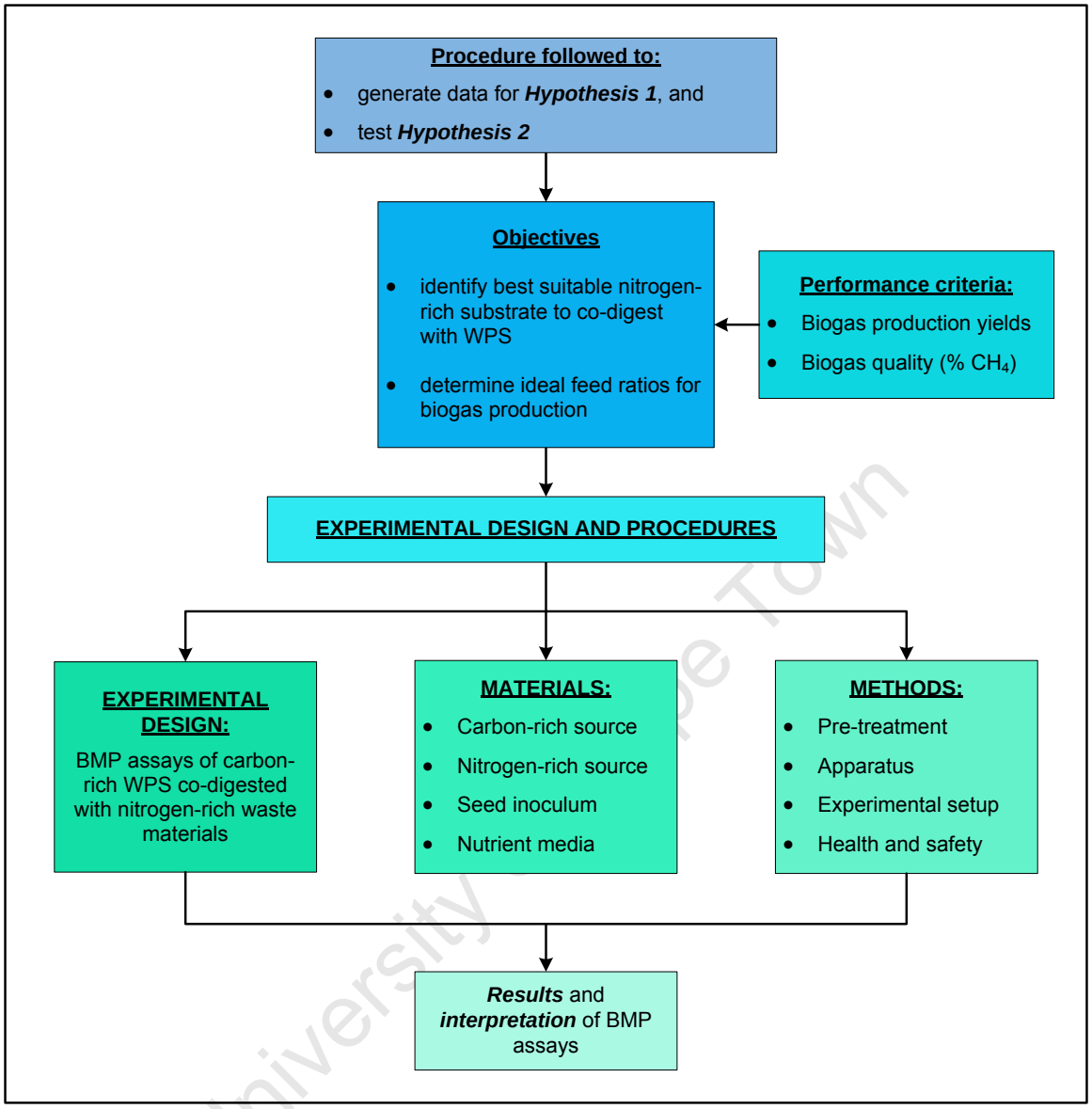


Figure 3-1: Schematic of the procedure followed to test Hypothesis 2

The second procedure presented in Figure 3-1 builds on that of a Life Cycle Assessment (LCA) framework (Figure 2-12), detailed in the ISO 14040standard. This procedure addresses *Hypothesis 1*, but also expands on the results obtained through the testing of *Hypothesis 2* to further assess the effects that co-digestion may have on the life cycle performance of the biogas-based end-use applications

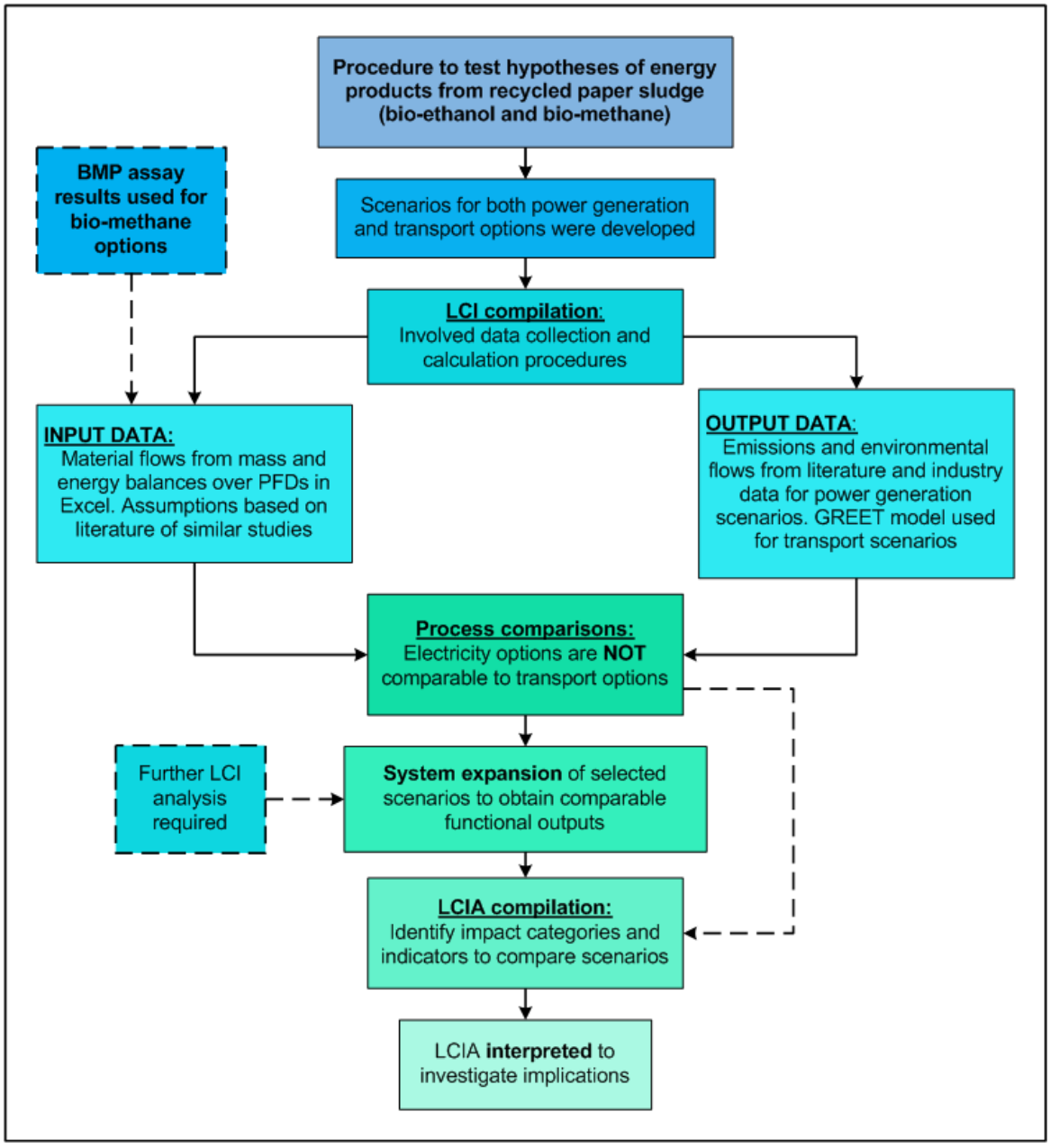


Figure 3-2: Schematic of the LCA procedure followed to test the hypotheses (adapted from Melamu and von Blottnitz, 2008)

The first task, based on the LCA framework, was therefore to define the goal and scope of the study, which is covered in Section 3.3. This includes the development of the biogas- and bio-ethanol-based scenarios that were subsequently modelled and compared to address the hypotheses. The next phase in the LCA framework is the *life cycle inventory analysis* (LCI), which is presented in Chapter 6, followed by the *life cycle impact assessment* (LCIA), presented in Chapter 7. The final *interpretation phase* depicted in the LCA framework (Figure 2-12) is performed throughout Chapters 6 and 7, but is summarised and discussed in Section 7.3.

With respect to the remainder of this chapter, Section 3.4 describes the procedure undertaken to compile the LCI for the life cycle assessment, which involves some experimental work to generate primary data for the population of the inventory. Section 0 presents and describes the approach of system expansion, which was implemented to compare the bio-methane and bio-ethanol product outputs. This is followed by a description of the method adopted to assess the environmental impacts of the selected systems (*LCIA*) in Section 3.6. Finally, this chapter closes off with an outlook for Chapters 4 and 5, as well as how these chapters fit into Chapters 6 and 7.

3.3 Goal and Scope Definition

3.3.1 Goal of the Life Cycle Assessment

The primary goal of the LCA is to explore the life cycles of the competing systems of ethanol or biogas production from waste paper sludge (WPS) feedstock and the uses of these energy products, and to compare them based on their projected impact on the environment. The two bio-energy options will also be assessed with regard to the technical viability of both the process and their end use of either power generation or transport fuel.

This particular comparative LCA study is classified as an attributional LCA as average data is used. To effectively compare the two technologies and substantiate the hypotheses put forward within the context of a coal-intensive South African context. The following goal statements were proposed to test *Hypothesis 1* and *Hypothesis 2*, respectively. These scenarios are further discussed in the next Section.

SYSTEM 1: Five scenarios were developed to test the first hypothesis, which is essentially for the pure or uncontaminated WPS. Two of these involve the production of bio-methane through the mono-digestion of WPS for the co-generation of power and heat. The other three scenarios entail the production of bio-ethanol from WPS for power generation or for transport fuel, which will be further discussed in subsequent sections.

SYSTEM 2: Two additional bio-methane scenarios were developed, along with those considered in *Hypothesis 1*, two scenarios involving the production of bio-methane through the co-digestion of WPS and abattoir waste (AW) for the cogeneration of power and heat were developed to assess the effects of co-digestion on the end-use performance.

The intended audiences are:

- Researchers in the bio-energy sector, particularly the “energy from waste” knowledge sector;
- Strategists involved in energy initiatives in South Africa, especially those interested/focused on renewable energy;
- Industries who are interested in branching out from their current use of by-products or waste streams into energy products, e.g. waste paper sludge from paper recycling plants.

3.3.2 Scope & modelling

3.3.2.1 Functional unit

Energy from waste (EfW) projects provides a dual functionality: they provide a waste management service and they yield one or more energy products. As these functionalities are linked by the energetic efficiency of the conversion process, the modeller has to choose one of the functions as the basis for the comparison. In the LCA done here, the unit for the comparison is based on the waste treatment service. Different types and amounts of energy products arise in different EfW scenarios. For the transport options the service measured is the distance driven by a light-duty vehicle (km driven), and for the power generation options the energy service will be measured by how many MJ of electricity is generated.

The reference flow selected for this study was 67 tons of raw WPS per day. This was based on 40% of the daily output at Nampak Tissue; the share that is sent to landfill for disposal. The remaining 60% is given to a company for private purposes (name unspecified). The landfill site is situated in Vissershok and has a maximum capacity of 2 years; after which the waste will need to be dumped at Piketberg at an additional cost for Nampak Tissue.

3.3.2.2 Level of detail

For the purpose of this study first order input/output mass and energy balances of the proposed fuel production and use systems are deemed sufficient to obtain meet the stated goals of the study. This implies that for any comparative results within 10% of each other, no significant difference between options may be concluded. For an advanced LCA, more detailed analysis would be required.

3.3.2.3 System boundaries

The system boundaries define which processes to include in the environmental analysis. The two systems under consideration here are the production of bio-ethanol and biogas from paper sludge. With the preferred energetic usage of these two products being different, the analysis boundaries need to be drawn to include not only the operation of the bio-energy production plant and fuel upgrading but also the end-use of bio-energy (see Figure 3-3 and Figure 3-4 below).

The system boundary includes the emissions associated with the production of the system inputs used in the calculations, such as fossil energy carriers; but excludes that of the production of WPS and AW inputs as both are waste flows and thus considered to carry none of the environmental burden associated with their respective processing plants. The landfilling of any waste sludge produced during digestion is considered within the system boundaries, thus contributing to emissions.

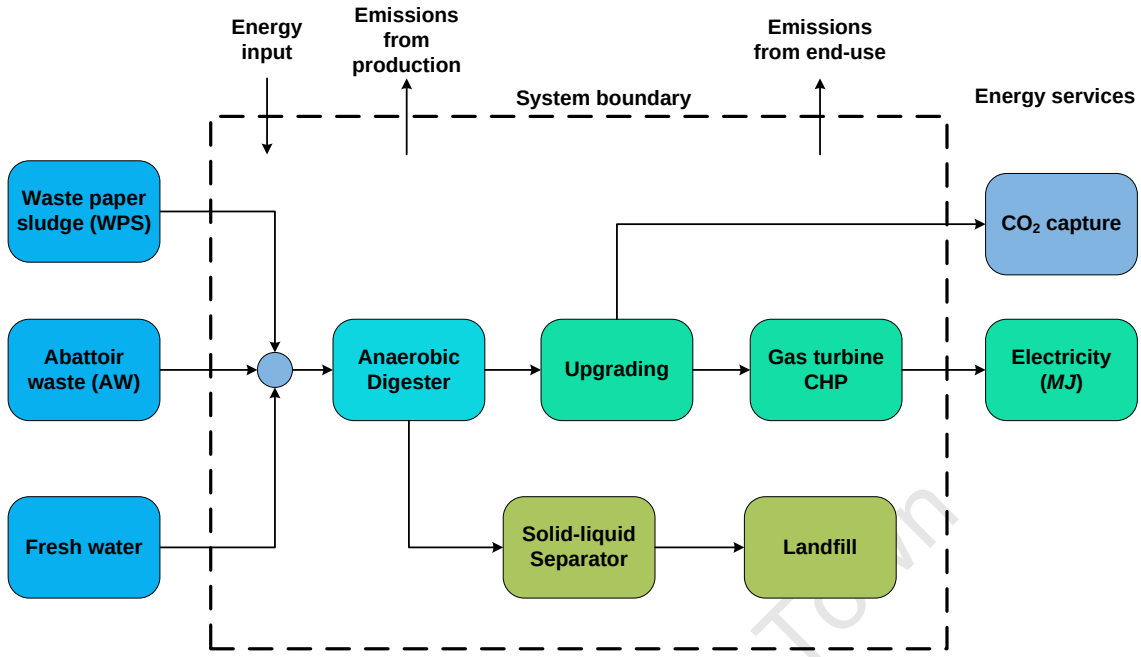


Figure 3-3: System boundary of biogas production from waste paper sludge

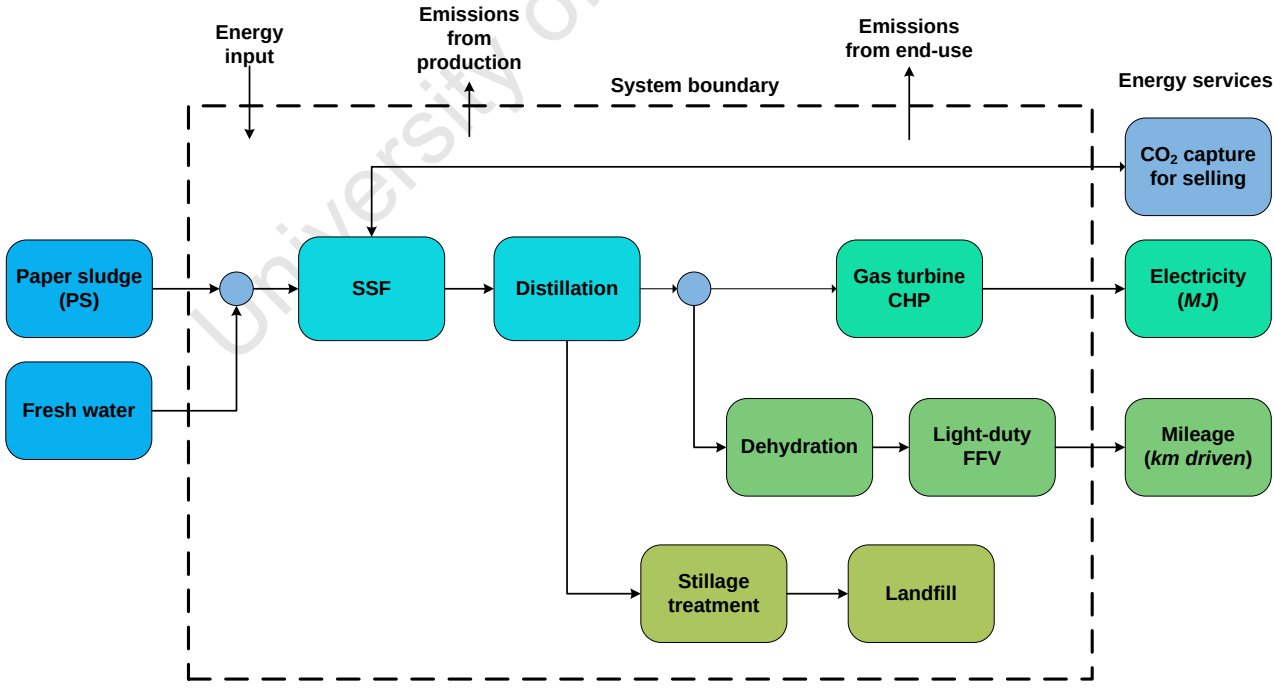


Figure 3-4: System boundary of ethanol production from waste paper sludge

The construction, maintenance and demolition of the bio-energy plants or of the infrastructure to be used, such as the case of distribution of the bio-energy, are considered to be outside of the scope of this study, and are thus excluded from the system. With regards to the time horizon, the focus of the study is essentially on short-term effects associated with introducing the bio-energy systems. The data used in the modelling phase was considered to be current.

3.3.2.4 System descriptions

This section considers the various scenarios developed for the testing of hypothesis 1 (SYSTEM 1) and hypothesis 2 (SYSTEM 2). This includes a brief description of each scenario and the justification for its use.

3.3.2.4.1 Scenario options developed for SYSTEM 1

The base case scenario for SYSTEM 1 is the use of bio-ethanol as a transport fuel for a light duty flexi-fuel vehicle (E-FFV, shown in Figure 3-5). The fuel ethanol is produced from WPS through combined hydrolysis and fermentation (SSF), the resulting stream is distilled to achieve 95% ethanol-rich stream. A purity of at least 99.7% is required for use as a transport fuel (Elvers et al, 2008), which is achieved through dehydration. The vehicle technology was modelled with respect to the achievable mileage per MJ of ethanol produced and the associated emissions generated by the system.

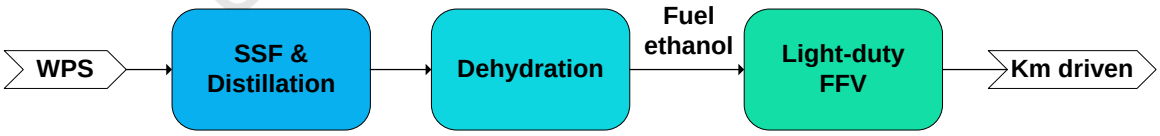


Figure 3-5: Transport scenario involving flexi-fuel vehicle powered by fuel ethanol (E-FFV)

Ethanol would preferably be used as a gasoline additive based on its extensive application as such (see Section 2.3 for description of current applications). However, following Melamu (2008) it is conceivable that it could be used to generate electricity, providing an easy comparison to the preferred usage of biogas. The electricity scenario (EE, shown in Figure 3-6) involving ethanol from WPS includes the conversion of 95% ethanol-rich stream to electricity using a 35% efficient gas turbine. A fraction of this electricity is used in the production phase; details on these calculations will be presented in Chapter 6.

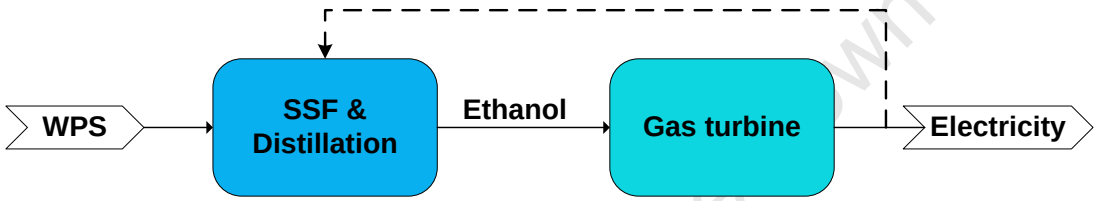


Figure 3-6: Electricity scenario involving ethanol from paper sludge (EE)

An alternative scenario (EE-HI, shown in Figure 3-7) includes the production of biogas from the process waste sludge and its subsequent use for the co-generation of additional electricity and heat for integration into the system. Similarly to the previous scenario, a fraction of the electricity will be integrated into the production phase.

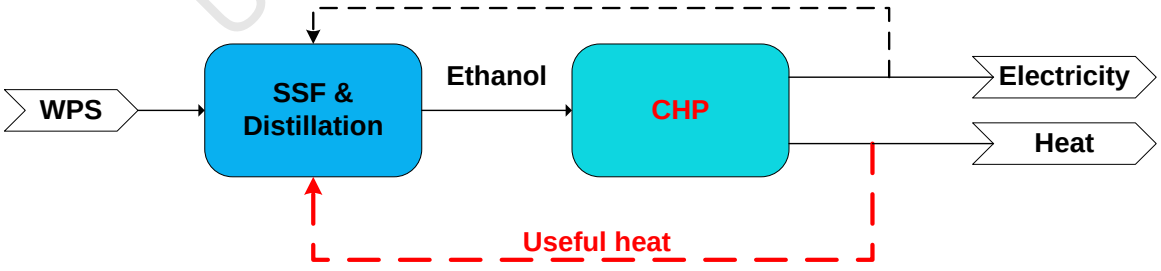


Figure 3-7: Electricity scenario with heat integration involving ethanol from paper sludge (EE-HI)

Two electricity options from biogas were investigated; both involving biogas produced through the mono-digestion of WPS (MBE and MBE-HI, shown in Figure 3-8). These scenarios include the upgrading of the biogas to 60% CH_4 through scrubbing. The resulting CH_4-enriched biogas is then considered for the co-generation of electricity and heat. As with the ethanol-based electricity scenario, a fraction of the electricity generated will be used to satisfy the production requirements. The second scenario (MBE-HI) involves the integration of biogas-based heat to satisfy the thermal requirements of the production process.

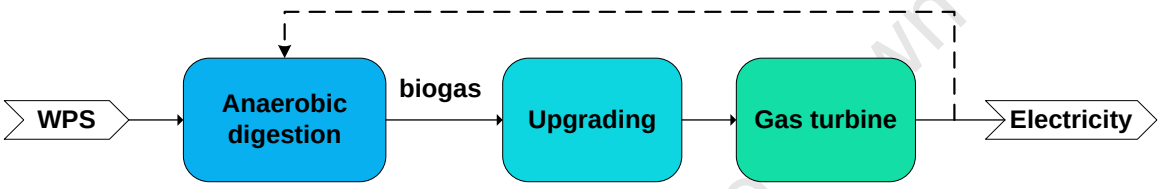


Figure 3-8: Electricity scenario involving biogas from mono-digestion of paper sludge (MBE)

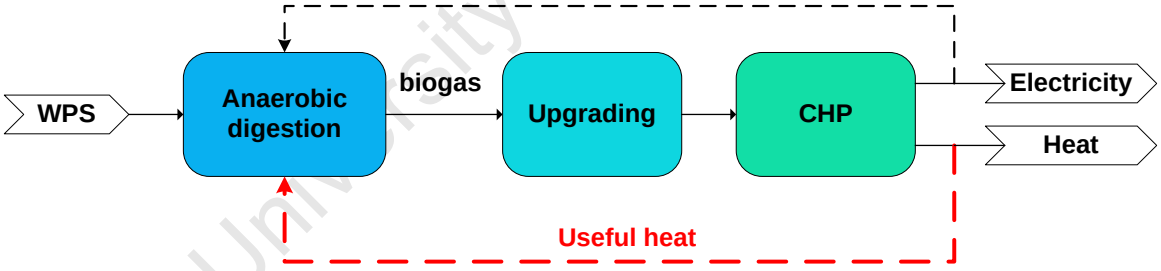


Figure 3-9: Electricity scenario with heat integration involving biogas from mono-digestion of paper sludge (MBE-HI)

Bio-methane for vehicles was not considered in this scenario as the switch from light-duty to heavy-duty would complicate the comparison too much.

3.3.2.4.2 Scenario options for SYSTEM 2

For SYSTEM 2, the base case scenario is the mono-digestion of WPS for biogas to be used for the co-generation of electricity and heat, (MBE, shown in Figure 3-8) and with heat integration (MBE-HI, shown in Figure 3-9). To assess the effects of co-digestion of WPS with abattoir waste (AW) two additional scenarios were developed (CBE and CBE-HI, shown in Figure 3-11). As concluded in chapter 5, the latter displayed the best results per unit digester volume for the co-digestion scenarios as well as the biggest improvement with respect to the expected yield.

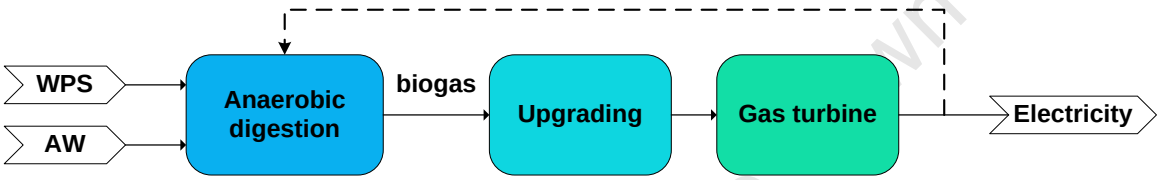


Figure 3-10: Electricity scenario involving biogas from co-digestion of paper sludge and abattoir waste (CBE)

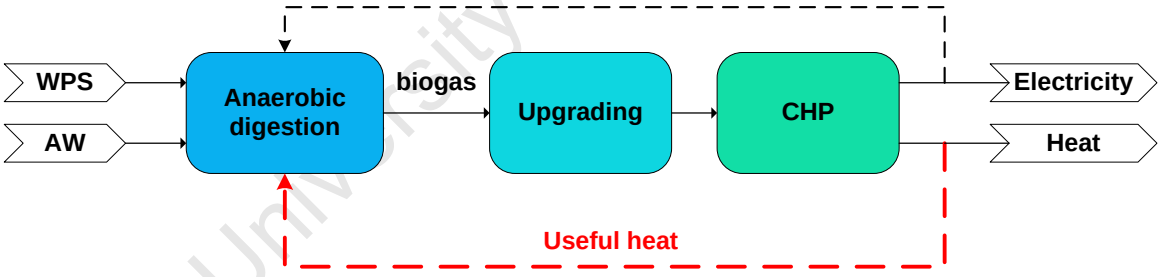


Figure 3-11: Electricity scenario with heat integration involving biogas from co-digestion of paper sludge and abattoir waste (CBE-HI)

As with the mono-digestion scenarios, both of these scenarios include the upgrading of the biogas to 60% CH_4 through scrubbing to be used for the co-generation of electricity and heat. The electricity is used to satisfy the energy requirements for both scenarios, and the heat is used for the thermal requirements in the other scenario (CBE-HI).

Further details will be presented in Chapter 6. The following sub-sections describe the approach used for inventory compilation and analysis, followed by the procedure of system expansion and the selected LCIA method.

3.4 LCI compilation procedures

The life cycle inventory involves the collection of data and calculation procedures to quantify relevant inputs and outputs of unit processes that are included within the system boundary. Based on this data, interpretations may be drawn, depending on the goal and scope of the LCA. This procedure is an iterative one and so may require modifications as it progresses due to limitations identified or new data requirements.

To generate the necessary data for the LCI a combination of secondary and primary data generation was used to populate the identified metrics. The primary data generation involved both process modelling and laboratory work, the latter is discussed further in Chapter 4.The approach of using a process flow diagram to model a process, using a *mass balance* or *material balance* is a popular approach to LCI compilation as computational tools such as Excel are readily available and easy to apply. The procedures are further discussed in subsequent sections.

3.4.1 Mass and energy balances for inputs

The primary data that was used for the material balance of the biogas production process was obtained from open source literature and from the experimental work. The data for the ethanol production process was obtained from open source literature as well. For the purpose of simplification and due to limitations during the LCI compilation procedure, assumptions were made for each process based on similar studies which will be further discussed in Chapter 6.

The basis for the material and energy balances for both energy conversion processes corresponds to 67 tons of PS feed per day, the reference flow chosen for the LCA. The modelling of the material flows of the processes will be presented in Chapter 6, along with the assumptions made and limitations encountered. On completion of the mass and energy balances over these process flow diagrams, the following data is obtained:

i. Amount of water utilised by both processes
ii. The production volumes of ethanol and biogas through their respective processes
iii. The amount of sludge generated in the bio-energy production processes
iv. The amount of biogenic carbon dioxide produced in the production phase
v. The process heat and electricity requirements
vi. Energy yields of the systems

3.4.2 Outputs compilation

The material and energy balances provide the data for the input of the LCI, but not all the emissions associated with the production processes and bio-energy applications is included in this approach. As mentioned previously, scenarios were developed for the two different applications of the bio-energies, namely that of electricity generation and transport options. For the coal-based powered applications, published data was used (Eskom, 2006). Emission data from literature was used for the electricity and heat applications of both bio-energies.

With respect to the transport emissions, an approach using the Greenhouse Gases and Regulated Emissions and Energy use in Transportation (GREET) model was implemented (Argonne GREET model, 2006). No adjustments were needed to apply the data to Cape Town. The GREET model provides the fuel cycle of various types of vehicles which allows researchers to calculate the associated emission quantities. This will be further discussed in Chapter 6.

3.5 System expansion for comparing different energy products

As discussed in Section 2.7.2.3, when considering systems with multiple outputs or differing functional outputs the ISO standards recommend an expansion of the system boundary in question to include alternative ways to provide the additional functions so that all the scenarios yield comparable product outputs.

With respect to the first system, two end-use applications were considered, ethanol- and biogas-based electricity generation and the use of bio-ethanol as a transport fuel. The functional units considered were electric energy generated (MJ) and mileage achieved (km driven), respectively. Clearly these energy services are not directly comparable and so the conventionally used fossil-based alternatives, gasoline vehicle fuel and coal-based electricity generation, were used to obtain the expanded system functionality (shown in Figure 3-12) as devised by Melamu (2008).

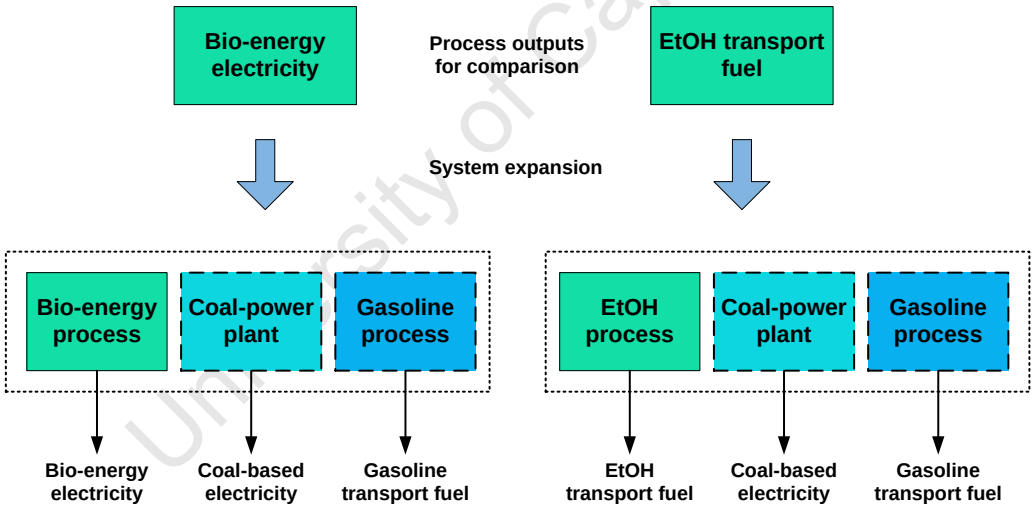


Figure 3-12: Schematic of approach to expansion of SYSTEM 1 (compiled using Melamu, 2008)

The base case scenario for SYSTEM 1 was the electricity generation scenario involving mono-digestion WPS with a set reference flow of 67 tons of WPS per day. As stated in *Hypothesis 1*, the performance of the various options was to be compared per unit digester volume. Therefore, it was necessary to scale the co-digestion scenario to a

combined feed of WPS and AW that correlates with the digester volume of 67 tons of WPS feed for the mono-digestion scenario. In addition to this, the scenarios yielded outputs of different magnitudes and thus were incomparable. To overcome this challenge, the traditionally used fossil-based alternative, in this case coal-based electricity was added to achieve the expanded product output (shown in Figure 3-13 below).

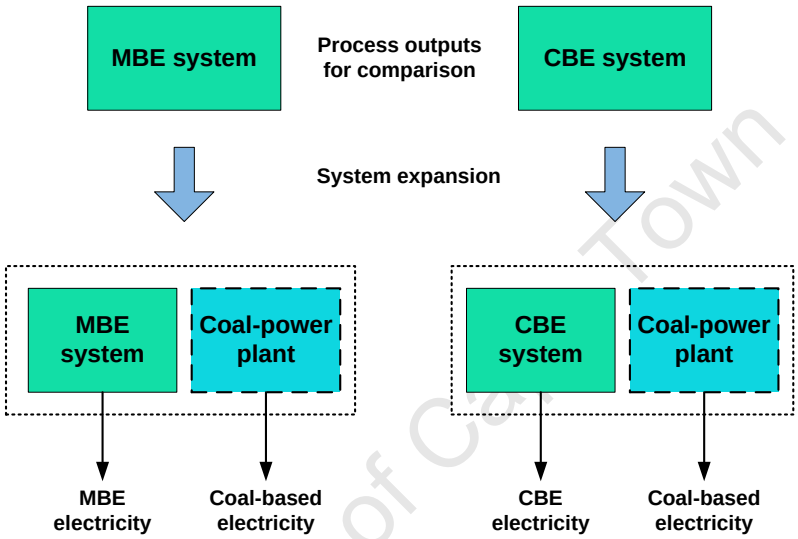


Figure 3-13: Schematic of expansion of bio-methane SYSTEM 2 (compiled using Melamu, 2008)

The following section presents a detailed description of the methods chosen for the impact analysis phase.

3.6 LCIA method

The phase of inventory analysis identifies and quantifies the inputs from the environment and the emissions and wastes discharged to the environment, generating an inventory table which lists the usage of resources and emissions associated with the provision of one functional unit.

To assess this large quantity of data, estimates are made of how each input and emission contributes to a set of recognised environmental impacts or themes. The purpose of an LCIA method is to examine these impact categories as well as the relevant category indicators connected with the LCI results, so as to provide information for the Life Cycle Interpretation phase.

The general framework of the LCIA phase consists of several mandatory elements. In addition to this there are optional elements for normalization, grouping or weighting of the indicator results and data quality analysis techniques. The following elements, however, are mandatory, as set out by the ISO 14042 standard:

i. Selection of impact categories, category indicators and characterization

ii. Assignment of LCI results (classification) to the impact categories

iii. Calculation of category indicator results (characterization)

The impact assessment method chosen to quantify the impact categories was the CML 2 baseline 2001 V2.03 as it met all these mandatory requirements and the baseline version is more suitable for a study of this scope. Furthermore, it follows a problem oriented method with the set of category indicators defined for the midpoint approach, which falls in line with the goal and scope of the study.

3.6.1 Impact categories selected for this study

3.6.1.1 Global warming potential

The global warming potential is related to the emissions of “greenhouse gases” to air, which can result in adverse effects upon the ecosystem, human health and material welfare. These gases include carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_XO). The impacts associated with greenhouse gas are compared to the warming potential of carbon dioxide and are thus expressed as CO_2 equivalents.

3.6.1.2 Human toxicity

This category concerns the negative effects of various toxic chemicals on the human health, excluding those associated with localised use of chemicals in the working environment, but focusing rather on the effects of long-term exposure of chemicals in the regional and global environment.

3.6.1.3 Photochemical ozone creation

The formation of reactive substances (mainly ozone) within the troposphere from chemicals such as nitrogen oxides (NO_X), carbon monoxide (CO), methane (CH_4) and other volatile organic compounds in the presence of high temperatures and sunlight (Von Blottnitz and Curran, 2007). The resulting smog may lead to negative effects on human health and the ecosystem.

3.6.1.4 Fresh water aquatic eco-toxicity

Eco toxicity characterization provides a relative prediction of a chemical's ability to cause harm to plant and animal life. This category indicator refers to the impact on fresh water ecosystems, as a result of emissions of toxic substances to air, water and soil. Eco-toxicity Potentials (FAETP) are calculated with USES-LCA, describing fate, exposure and effects of toxic substances. Characterisation factors are expressed as 1,4-dichlorobenzene equivalents.

3.6.1.5 Acidification

Acidifying substances cause a wide range of impacts on soil, groundwater, surface water, organisms, ecosystems and materials (buildings). They result from the reaction of water vapour with sulphur dioxide and nitrogen oxides that reach the atmosphere. Acidification Potentials (AP) compare the capacity of substances to release hydrogen and is expressed as SO_2 equivalents (Von Blottnitz and Curran, 2007).

3.6.1.6 Eutrophication

Eutrophication includes all impacts due to excessive levels of macronutrients in the environment caused by emissions of nutrients to air, water and soil. Nutrification potential (NP) is based on the stoichiometric procedure of Heijungs and Suh (1992), and expressed as PO_4 equivalents.

3.7 Outlook

The literature review identified a gap in the literature with respect to the production of biogas from WPS and as discussed in Section3.4, for the LCI compilation procedure, laboratory work would be necessary to identify the biogas systems of interest and the possible biogas yields that can be achieved. Chapter 4 describes the design of the necessary experimental work, together with a detailed description of the methods implemented and materials used. The results of the experimental work are then presented in Chapter 5, along with a detailed discussion and concluding remarks.

This chapter formulated two hypotheses to be tested based on the findings of literature review and developed a methodology which builds on that of a Life Cycle Assessment framework. The first phase, the *Goal and Scope Definition*, was completed providing the bio-methane and bio-ethanol system scenarios necessary for comparative analysis. This was followed by the procedures and methods used for the LCA.

Based on the now defined problem, the second phase of the LCA framework, the *inventory analysis* was carried out in Chapter 6; followed by the *impact assessment* and *interpretation* in Chapter 7. The dissertation is concluded by compiling and presenting the overall findings, along with recommendations, based on these findings.

4 EXPERIMENTAL METHODS AND MATERIALS

Based on the literature review of the bio-ethanol and bio-methane studies involving waste paper, cellulosic waste paper sludge was identified as a very attractive option for the former as it requires no further size reduction and therefore saves on both energy and enzyme costs. On the other hand, studies involving the conversion of waste paper sludge to biogas was sorely lacking, however, waste paper proved an attractive carbon-source for biogas production (Gunaseelan, 2006; Yen *et al*, 2007; Siddiqui et al, 2011). The following hypothesis was therefore put forward:

> *Forms of non-recyclable and non-recoverable paper which are more contaminated will co-digest well in anaerobic digesters set up to recover energy from waste and reduce volumes for disposal, boosting gas yields per unit of digester volume, especially when used to adjust carbon to nitrogen ratios.*

The aim of the experimental work was to characterize the Bio-chemical Methane Potential (BMP) of waste paper sludge co-digested with nitrogen–rich substrates at 100 ml scale, in duplicate and under mesophilic conditions (37°C). The control parameters investigated were pH, feed ratio, % CH_4, biogas yield, TS and VS.

The objective of this experimental work was therefore to:

- identify which nitrogen-rich substrate is best suited to co-digest with PS in terms of biogas production yields and quality; and
- determine what feed ratios are ideal for biogas production

4.1 Materials

The substrates under consideration are two types of *waste paper sludge* (WPS), PM-2 and PM-4, both collected from the Nampak Tissue Plant located in Bellville Industria. The PM-2 plant uses virgin material as feedstock whereas the PM-4 plant uses recycled material as feedstock.

The nitrogen-rich materials that were used for co-digestion with RPS were fish waste and abattoir waste. The fish waste (FW) consisted mainly of skin, bones, intestines and other unusable off cuts. It was procured from Fish 4 Africa located in Hout Bay. The sample of abattoir waste (AW) contained blood, intestines and other unusable off cuts and was procured from Asdam Abattoirs in Ceres. All substrates were characterised with respect to volatile solids and total solids (Table 4-1). Detailed results of the characterisation methods are presented in the Appendices.

Table 4-1: Volatile solids (VS) and total solids (TS) characterisation of feed substrates (Run 1)

Description			*Moisture content [%]*	*Total Solids [% TS]*	*Volatile Solids [%VS of TS]*
Recycled or waste paper sludge	Pulp from virgin feedstock	PM2	68	32	97
		PM2n	67	33	67
	Pulp from recycled feedstock	PM4o	52	48	31
		PM4n	60	40	41
N-rich substrate	Fish waste	FW	79	21	90
		FWn	78	22	89
	Abattoir waste	AW	79	21	83

It is worth noting that the paper sludge from the virgin paper production is significantly higher (if variable from 67 – 96%) in volatile solids than the sludge from processing of

recycled paper (31 - 40%). This is probably due to the presence of mineral fillers in some of the grades of recycled paper, resulting in this sludge having a high ash content.

The inoculums were sampled from the AD at Newlands plant of the South African Breweries (SAB) and from the digester installed at the Marquard Residence (MARQ). The SAB inoculum was primarily fed sugars and other easily digestible carbohydrates; whereas the Marquard inoculum used raw cow dung as a seed inoculum and is primarily fed food waste such as plate scrapings or vegetable peels. A prescribed inoculum-to-feed ratio of 1.5:1 based on the volatile solids (VS) of the materials was used (Yunquin *et al,* 2009).

4.2 Methods

The protocol followed here for bio-methane potential (BMP) analyses of paper waste will be done as set out by Angelidaki *et al* (2009) and Owen *et al* (1979).

4.2.1 Pre-treatment

The paper sludge was not submitted to any pre-treatment, however due to the heterogeneous nature of the fish waste (FW) it was necessary to process it. A simple food processor was used in this case, creating a fairly homogenous paste. The abattoir waste (AW) was sterilized at 120°C for 1 hour prior to entering the 37°C room.

Neither inoculum was acclimatized to the substrates, but were sparged with nitrogen gas and allowed to incubate in the 37°C room for several days prior to the commencement of the BMP assays until the production of methane had ceased. The inoculums were also characterized with respect to the TS and VS so as to determine the necessary feed mass of the substrates with respect to the 1.5:1 feed-to-inoculum ratio.

4.2.2 BMP assays

The following tables show the configurations for the various runs of the experiments. Run 1 was the first phase of experiments, a full run of 38 assays[1] with the SAB inoculum. The 2nd run involved a repeat of the 1st run with the inoculum from the Marquard Digester.

Table 4-2: Configuration of Run 1 – BMP assays with SAB inoculum

Materials					
	Blank	A1	A2		
	Control	A3	A4		
No co-digestion	PM2	A5	A6		
	PM4o	A7	A8		
	PM4n	A9	A10		
	FW	A11	A12		
	AW	A13	A14		
Co-digestion		**(3:1)**		**(6:1)**	
PM2	FW	A15	A16	A17	A18
	AW	A19	A20	A21	A22
PM4o	FW	A23	A24	A25	A26
	AW	A27	A28	A29	A30
PM4n	FW	A31	A32	A33	A34
	AW	A35	A36	A37	A38

[1] An assay involves the procedure of testing or measuring the activity of a drug or biochemical in an organism or organic sample.

Table 4-3: Configuration of Run 2 – Repeats of Run 1 with Marquard Inoculum

Materials					
	Blank	C1	C2		
	Control	C3	C4		
No co-digestion	PM2n	C5	C6		
	PM4o	C7	C8		
	PM4n	C9	C10		
	FW	C11	C12		
	AW	C13	C14		
Co-digestion		**(3:1)**		**(6:1)**	
PM2n	FW	C15	C16	C17	C18
	AW	C19	C20	C21	C22
PM4o	FW	C23	C24	C25	C26
	AW	C27	C28	C29	C30
PM4n	FW	C31	C32	C33	C34
	AW	C35	C36	C37	C38

Based on some interesting results for digestion involving PM2 and FW for the 1st run, repeats were performed with a new sample of the SAB inoculum for both the mono- and co-digestion of PM2 resulting in 18 assays altogether.

Table 4-4: Configuration of Run 3 – Repeats of BMP assays with PM-2n sludge and SAB inoculum

Materials					
	Blank	D1	D2		
	Control	D3	D4		
No co-digestion	PM2n	D5	D6		
	FW	D7	D8		
	AW	D9	D10		
Co-digestion		**(3:1)**		**(6:1)**	
PM2n	FW	D11	D12	D13	D14
	AW	D15	D16	D17	D18

A basis of 1 g VS total feed is added to each assay. With respect to the co-digestion, 3 or 6 parts RPS was added to 1 part of the respective nitrogen-rich substrate (FW or AW)

on a g VS basis. A nutrient medium consisting of nutrients/ micronutrients/ vitamins was made up to ensure optimal function of anaerobic microorganisms (Angelidaki *et al*, 2009). The various solutions were made up to the specifications in Table 4-5 below.

Table 4-5: Nutrient media make-up (Angelidaki *et al*, 2009)

Chemical(s)	*g in 1L*	*Conc.*	*mL /100 mL*
KH_2PO_4	0.27	100	1
$NaHPO_4$-$12H_2O$	1.12	100	1
NH_4Cl	0.53	100	1
$CaCl_2$-$2H_2O$	0.075	100	1
$MgCl_2$-$6H_2O$	0.1	100	1
$FeCl_2$-$4H_2O$	0.02	100	1
Resazurin (O_2 indicator)	0.001	100	1
Na_2S-$9H_2O$	0.1	50	2

The "seed-blank" assay contained only the inoculum and media, with the remainder of the volume made up of water. This was used to determine the "background value" or reference value and subsequently subtracted from the methane production of each BMP assay to give the resultant volumes (Owen *et al*, 1978). The "control" consisted of the medium, inoculum and glucose instead of the substrate, as this gives an indication of the inoculum response to standard substrates. Each assay was performed in duplicate.

4.2.3 Apparatus and experimental setup

The experimental setup consisted of a series of sterilized Pyrex bottles with rubber stoppers and aluminium crimps. Each bottle has a total capacity of 125 mL, a working volume of 100 mL and gas phase of 25 mL. To ensure a limited amount of oxygen is present in the flask, it will initially be sparged with N_2/CO_2 (80/20 % volume). The inoculum and nutrient-substrate mixture was transferred to the assay bottles and sparged again before finally sealing the vessels to ensure pH neutrality. N_2/CO_2 gas is typically flushed in the headspace of the inoculum and substrate storage vessels as well before transfer to the assay vessels. Na_2CO_3 solution was added as a buffer to the control runs,

to ensure a pH of ~7.1 – 8. Na_2CO_3 solution was not added to the runs containing RPS as it already contains a high percentage of $CaCO_3$, which serves as a buffer. No further pH control was implemented throughout the experimental cycle.

The sealed Pyrex bottles were then stored in the 37°C room for approximately 60 days, or until gas production ceased. BMP is referenced in various ways, in this case it was referenced to sample mass (mL CH_4/kg VS_{FED}). To obtain this, the biogas produced was collected from the gas phase accumulated in the headspace of the assay bottles on a daily basis and measured using a volumetric method of displacement. A measuring cylinder is immersed in a coloured, acidic bath of pH 4 to minimize dissolution of CO_2. The cylinder is connected via rubber tubing to a syringe and needle which is used to puncture the rubber stoppers.

On a weekly basis a sample was extracted and measured for % CH_4 by gas chromatography (GC) using the Perkin Elmer GC System with a Forte Sol Gel WAX Capillary Column. The samples were taken with a 100µL Hamilton syringe.

4.2.4 Health and safety

The correct protective wear was worn at all times as some of the chemicals used are corrosive and substrates unhygienic. A lab coat, gloves, safety glasses and closed shoes were required to be worn when handling them in case of spillage.

The biological waste generated from the experiments was disposed of in the correct manner; that is sterilization with the necessary chemicals and/or incineration. There is the risk of fire or explosion if the biogas is exposed to a flame. The measurements of the biogas was therefore conducted in a fume hood, also as it has an unpleasant smell. The 37°C room is well ventilated, which ensured that the gas was sufficiently extracted. There is also a risk of asphyxiation when dealing with large amounts of N_2/CO_2 gas and the necessary safety measures were adhered to.

The following chapter presents and discusses the results obtained after the entire 60-70 day duration of the experiments.

5 EXPERIMENTAL RESULTS AND DISCUSSION

The cumulative biogas production of the experiments was plotted over the 60 day duration of the experiments for each substrate mix. The results for the first run are graphically presented in the following section, to illustrate the behaviour of the bio-methane potential assays. Duplicates for each feed mix is included; the markers of which are the same colour and shape, one open and the other closed to indicate the difference between duplicates.

5.1 Cumulative biogas production with SAB inoculum

The reference assays (blanks) for this run produced no gas and therefore was not plotted. The volumes produced were thus taken as the final biogas yields. The first set of assays are those involving mono-digestion of the various substrates, all paper sludge and nitrogen-rich materials.

Figure 5-1 (a) illustrates that the FW yielded the lowest biogas yields. This corresponded to an average of 129 mL/g VS_{FED} of FW; whereas the mono-digestion of AW yielded a maximum of 590 ml/g VS_{FED}. An interesting observation is that the PM2, FW and the control (1 g VS of pure glucose) showed a first plateau in production within the first 10 days, followed by a second increase shortly after that. A possible reason for this is very fast digestion of shorter chain carbohydrates in the substrate, followed by a "slump" due to the slower digestion of the longer carbohydrates which progresses from the 10^{th} day. An alternative explanation could be a pH drop causing the "slump" in production, and the system correcting itself during the first plateau, followed by the "second" increase. This would explain the observed dynamics of the "control".

The next set of BMP assays is that involving the co-digestion of PM2 (virgin material feed) and both FW and AW. Figure 5-1 (b) shows the feed mixture with the highest average yield is that of the co-digestion of PM2 and AW for both the 3:1 and 6:1 ratios, with average yields of 616 mL/g VS_{FED} and 663 mL/g VS_{FED}, respectively. The co-digestion of PM2 and FW (3:1) is the lowest yield achieved for this set, at 506 mL/g

VS_{FED}. The observation made earlier with the previous set is repeated with the co-digestion of PM2 and FW for both 3:1 and 6:1 feed mixes.

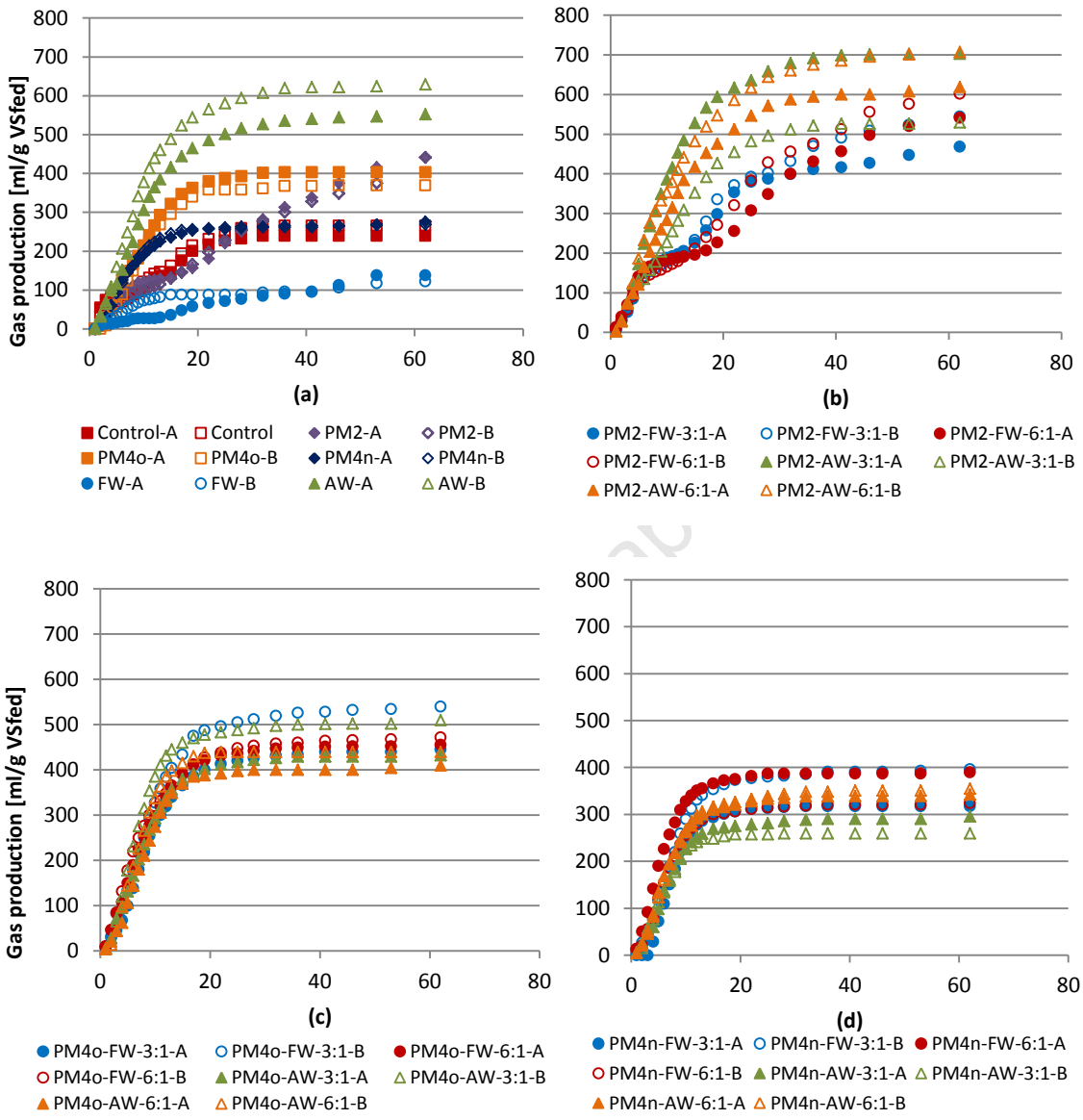


Figure 5-1: Plot of cumulative biogas production for Run 1 with SAB inoculum: (a) mono-digestion; (b) co-digestion with PM2; (c) co-digestion with PM4o; and (d) co-digestion with PM4n

Figure 5-1 (c) above illustrates the co-digestion with PM4o, where the prefix “o” and “n” distinguishes between the two batches of PM4 that was tested. The PM4o was an older

batch than PM4n; this former one had been stored in the laboratory freezer for 60 days prior to sampling the latter. The highest yield was 492 mL/g VS_{FED} from PM4o and FW (3:1), and the lowest was co-digestion of PMo and AW (6:1) with a yield of 424 mL/g VS_{FED}. It is also evident from the plot that the majority of the biogas production occurred in the first 20 days into the experimental run.

The final set consists of the co-digestion of PM4n with the nitrogen-rich wastes, with the co-digestion with FW (3:1) yielding the highest volumes of 357 mL/g VS_{FED} and the lowest for the co-digestion with AW (3:1) yielding 278 mL/g VS_{FED}. Production also slowed down significantly at Day 20 as with PM4o as is depicted in Figure 5-1 (d).

With respect to the *overall results*, the highest average yield of 663 mL/g VS_{FED} (616 mL/g VS_{FED} and 707 mL/g VS_{FED}) was achieved for the co-digestion of PM2 and AW in a 3:1 feed mix. The lowest average yield obtained for the co-digestion experiments was 278 mL/g VS obtained from a PM4n and AW mix (3:1). Overall, however, the mono-digestion of the FW resulted in the lowest average yield of 129 mL/g VS_{FED}.

5.1.1 Cumulative results for repeat run involving WPS and FW

As mentioned before, the repeat of the BMPs involving PM2 using SAB inoculum was performed so as to investigate the uncharacteristic biogas profiles achieved. It should be noted that new samples were collected for both PM2 and FW substrates, as well as the inoculum sample used. As can be seen in Figure 5-2 (a) below, the FW profile consists of two peaks similar to that achieved for Run 1.

The repeat run (Figure 5-2) resulted in higher biogas yields than Run 1, but nevertheless corresponded fairly well, except for that of the mono-digestion of the FWn which was 910 mL/ g VS_{FED} (627mL CH_4/ g VS_{FED}) in comparison to the mono-digestion of FW which was 129 mL/g VS_{FED} (102 mL CH_4/ g VS_{FED}). This could be due to the new sample of the fish waste as well as the new SAB inoculum sample, which appears to be more active than the first sample. The biogas profiles show that the biggest portion, up to 80%, of the

total biogas yield was produced within the first 10 to 15 days. The lowest yield obtained was for AW with 470 mL/ g $VS_{FED.}$

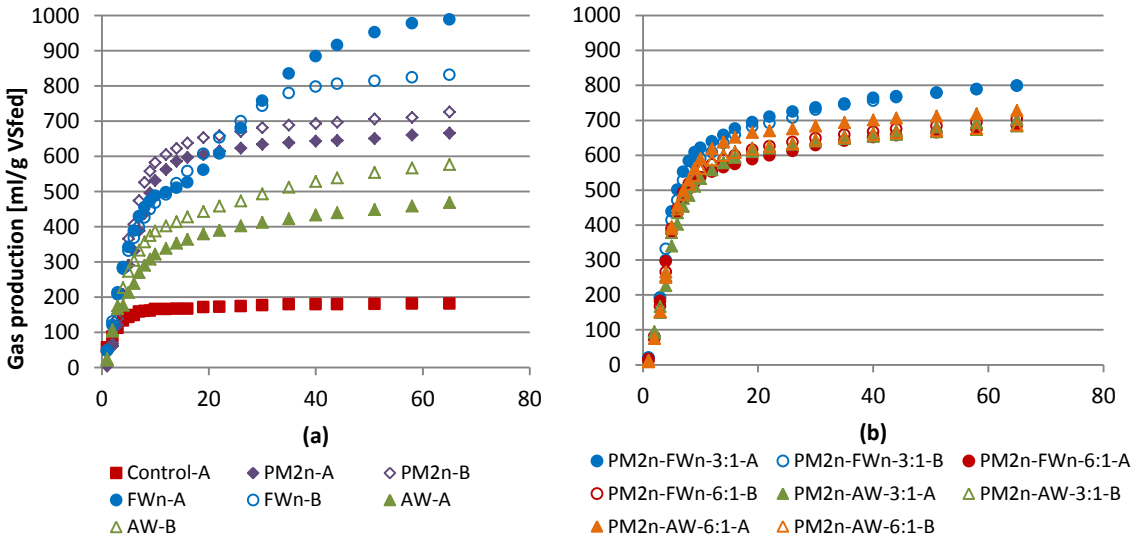


Figure 5-2: Plot of cumulative biogas production for Run 3 with SAB inoculum: (a) mono-digestion; and (b) co-digestion with PM2n

Otherwise the highest yield for co-digestion was 799 mL/ g $VS_{FED}$for the PM2n and FWn in a feed ratio of 3:1, whereas the lowest yield of 695 mL/ g $VS_{FED}$was obtained for that of PM2n and FWn in the 6:1 feed ratio. As is quite visible in Figure 5-2 the co-digestion curves closely match that of the mono-digestion of PM2n in both shape and biogas yields obtained over the run.

5.1.2 Cumulative biogas production with Marquard inoculum

As with the SAB inoculum, all the mono-digested substrates were plotted and compared.

Figure 5-3 (a) below shows that PM2n resulted in the highest biogas yield (639 mL/g VS_{FED}) and FW resulted in the lowest yield (77 mL/g VS_{FED}). There was also a large discrepancy between the yields obtained for the duplicates for mono-digestion of PM4o (227%), AW (236%) and FW (200%); as well as for one of the co-digestion sets PM4n-FW-3:1 (210%). The maximum yield of the two was used in further calculations.

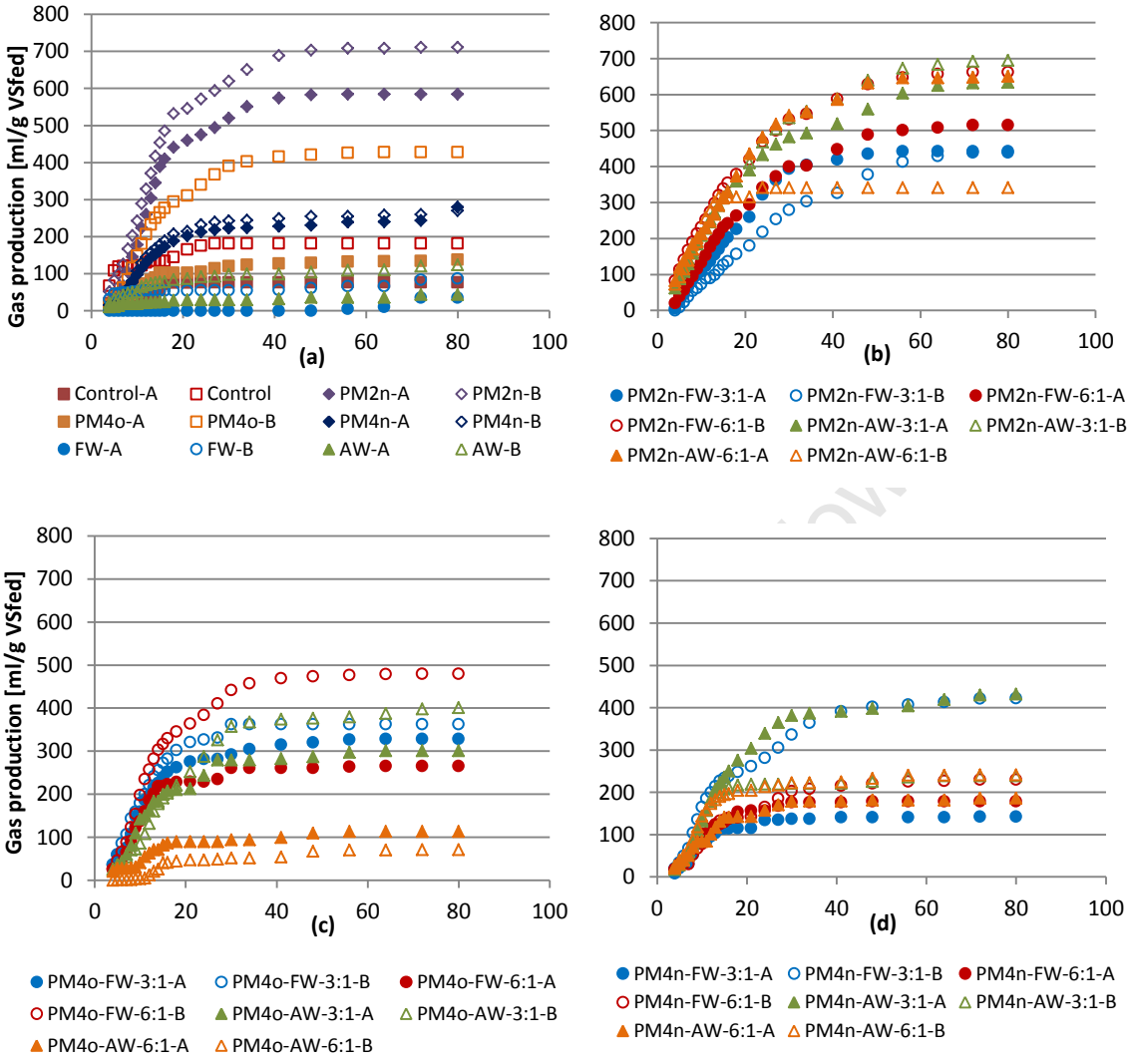


Figure 5-3: Plot of cumulative biogas production for Run 2 with Marquard inoculum: (a) mono-digestion; (b) co-digestion with PM2n; (c) co-digestion with PM4o; and (d) co-digestion with PM4n

With regards to the co-digestion experiments involving PM2n, the highest yield obtained was 655 mL/g VS_{FED} from co-digestion of PM2n and AW in 3:1 mix; whereas the lowest yield was 431mL/g VS_{FED} from PM2n and FW in a 3:1 mix. The gas production began to slow down at 20 days into the run already and had settled down by the 50th day, which is much the same as the mono-digestion set.

The highest average yield involving PM4o was 363 mL/g VS_{FED} from co-digestion with FW in a 6:1 feed mix; and the lowest average yield was 83 mL/g VS_{FED} from co-digestion with AW in a 6:1 feed mix. With respect to PM4n, co-digestion with FW in a feed mix of 3:1 resulted in the highest yield of 413 mL/g VS_{FED} whereas co-digestion with FW in a feed mix of 6:1 resulted in the lowest yield of 195 mL/g VS_{FED}.

Overall, the highest biogas yield was 655 mL/g VS_{FED} from the co-digestion of PM2n and AW (3:1 feed mix), with the lowest yield of 77 mL/g VS_{FED} corresponding to the mono-digestion of FW. The lowest yield from a co-digestion assay was 83 mL/g VS_{FED} from the 6:1 feed mix of PM4o and AW. It is clear that, as with the SAB inoculum, the PM2n RPS performs better than that of the PM4o or PM4n. All the sets within the run slowed down gas production by 20 days, producing on average 70% of the total biogas produced and up to 100% by day 50 for some BMP assays.

The following section describes the method used to calculate the overall methane content of the biogas produced to determine the methane yield per VS fed.

5.2 Determining the cumulative methane production yield

Gas chromatography analysis was performed on roughly a weekly basis. The % CH_4 obtained was then applied to the sum of the biogas volumes for that particular week to obtain a weekly methane volumes. The sum of these weekly volumes was used to determine the cumulative methane produced at the end of each run and thus the overall % CH_4. Figure 5-4 shows these weekly readings for various feeds obtained for Run 3. A clear trend is visible, showing rapid fluctuations during the first 10 – 15 days for all substrate feeds. A fairly consistent % CH_4 for the remainder of the experimental run is obtained for most substrate feeds, except that of the mono-digestion of the FW, which shows a substantial decrease.

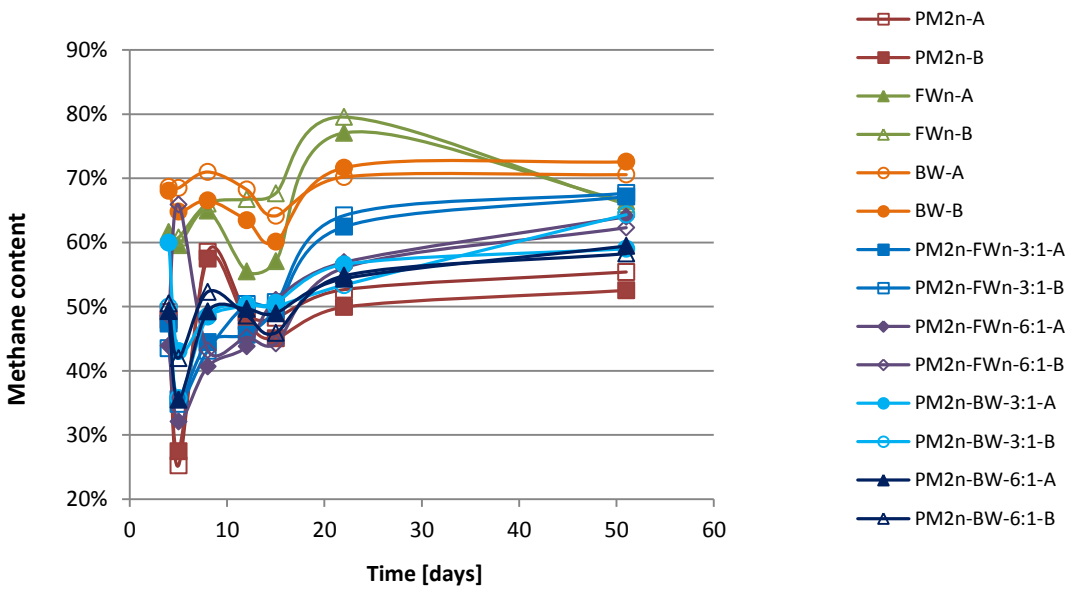


Figure 5-4: Plot of CH_4 content over the duration of experimental run 3

Table 5-1 below shows the total biogas collected for Run 3 with the SAB inoculum, the cumulative methane determined using the weekly GC readings and the overall % methane that was subsequently calculated. The maximum methane yield obtained was FWn with 595 mL/ g VS_{FED}. The highest yield for the co-digestion schemes is that of 371 mL/g VS_{FED} for PM2n and FWn in a feed ratio of 3:1 and the lowest yield was 333 mL/g VS_{FED} for PM2n and AW in a feed ratio of 6:1.

The highest methane compositions corresponded to that of the mono-digestion of AW and FW, the resulting 68.6% and 65.5% CH_4 respectively falls within the expected range for biogas from anaerobic digestion of 55 – 70 % (Deublein and Steinhauser, 2008).All the samples containing paper sludge obtained methane contents well below the expected range, the lowest of which was 44.9% for mono-digestion of PM2n.

Table 5-1: Overall methane yield [mL/g VS_{FED}] and % CH_4 for Run 3 based on GC results

	Total biogas [ml/ g VS_{FED}]			Total methane [ml/ g VS_{FED}]			Average % CH_4
			Average			**Average**	
PM2n	666	726	696	304	320	312	45
FWn	989	832	910	640	550	595	65
AW	469	577	523	325	392	359	69
PM2n-FWn-3:1	799	799	799	370	371	371	46
PM2n-FWn-6:1	686	704	695	296	385	341	49
PM2n-AW-3:1	703	684	693	362	319	340	49
PM2n-AW-6:1	729	687	708	334	333	333	47

Due to technical difficulties, weekly gas samples were not taken for Run 1, but instead a sample was taken on Day 41 of the 60 day run. Based on the trends observed for runs 2 and 3, for which weekly samples were taken, it was assumed that these values displayed in Table 5-2 closely correlate with the overall methane content of the biogas.The CH_4 % obtained for PM2-A was used as the average for the mono-digestion of PM2 because PM2-B had been contaminated and thus yielded a composition of only 3.53% methane.

The highest methane yield of 402 mL/g VS_{FED} corresponds to the co-digestion of PM2 and AW in a feed ratio of 6:1; whereas the lowest yield for co-digestion is 139 mL/g VS_{FED} for PM4n and AW in a feed ratio of 3:1. Some methane percentages were just below the expected range and many well below the expected range, the lowest of which was 45.8% for co-digestion of PM4o and AW in a feed ratio of 6:1. There was one extreme case of 78.6% CH_4 content for the mono-digestion of FW which is more than the expected range. As the CH_4 was only analysed once for this run, it should be noted that this 78.6% could be a maximum along the curve as is depicted in Figure 5-4 and further experiments are necessary to confirm these results.

Table 5-2: Overall methane yield [mL/g VS] and % CH_4 for Run 1 based on GC results

	% Methane			Total biogas [ml/ g VS_{FED}]			Methane [mL/g VS_{FED}]
			Average			**Average**	
PM2	-	-	52	441	441	441	231
PM4old	51	48	50	403	369	386	192
PM4new	51	50	50	275	268	272	137
FW	82	75	79	137	122	129	102
AW	62	59	60	552	629	590	355
PM2-FW-3:1	60	57	59	468	544	506	297
PM2-FW-6:1	65	51	58	541	602	572	328
PM2-AW-3:1	59	57	58	703	530	616	360
PM2-AW-6:1	63	59	61	619	707	663	402
PM4o-FW-3:1	55	54	55	444	539	492	270
PM4o-FW-6:1	53	45	49	455	471	463	225
PM4o-AW-3:1	55	52	53	432	509	471	250
PM4o-AW-6:1	50	41	46	409	439	424	193
PM4n-FW-3:1	60	59	60	318	396	357	212
PM4n-FW-6:1	57	49	53	390	324	357	189
PM4n-AW-3:1	52	48	50	296	260	278	139
PM4n-AW-6:1	57	56	56	342	355	348	197

The same method was used for Run 2 with the Marquard inoculum, the results of which are depicted in Table 5-3. As mentioned previously, the results for PM4o, FW, AW and the co-digestion of PM4n and AW (3:1) displayed >200% discrepancy, therefore the upper end of the range was used in these calculations.

A maximum methane yield for co-digestion was 407 mL/g VS_{FED} for that of PM2n and AW in a ratio of 3:1; and a minimum of 47 mL/g VS_{FED} for that of PM4o and AW in a feed ratio of 6:1. The majority of the methane percentages obtained was within the expected range, except for that of the mono-digestion of FW, PM4o and AW, which resulted in low of 39.3%, 54% and 50.3%, respectively.

Table 5-3: Overall methane yield [mL/g VS] and % CH_4 for Run 2 based on GC results

	% Methane			Total biogas [ml/ g VS_{FED}]			Methane [mL/g VS_{FED}]
			Average			**Average**	
PM2n	62	58	60	575	702	639	382
PM4o	-	-	54	-	-	419	226
PM4n	57	57	57	270	261	265	150
FW	-	-	39	-	-	77	30
AW	-	-	50	-	-	114	58
PM2n-FW-3:1	60	70	65	433	430	431	280
PM2n-FW-6:1	62	62	62	506	653	579	357
PM2n-AW-3:1	62	62	62	625	686	655	407
PM2n-AW-6:1	61	56	58	641	332	487	283
PM4o-FW-3:1	65	67	66	319	353	336	220
PM4o-FW-6:1	55	60	57	256	470	363	208
PM4o-AW-3:1	58	67	63	292	392	342	214
PM4o-AW-6:1	50	63	56	104	62	83	47
PM4n-FW-3:1	66	65	65	133	413	273	178
PM4n-FW-6:1	60	62	61	169	221	195	119
PM4n-AW-3:1	-	-	62	-	-	230	141
PM4n-AW-6:1	63	57	60	177	232	205	123

5.2.1 Effect of buffering on CH_4 content of biogas

As mentioned in the previous chapter, a Na_2CO_3 buffer was added only to those samples that did not contain waste paper sludge, as the latter was thought to contain a filler consisting essentially $CaCO_3$ which would serve as a buffer. It was suspected that the addition of carbonates may lead to the release of CO_2. The following figure illustrates the comparison of the average methane composition for those samples containing a buffer of Na_2CO_3 and those that received no buffering.

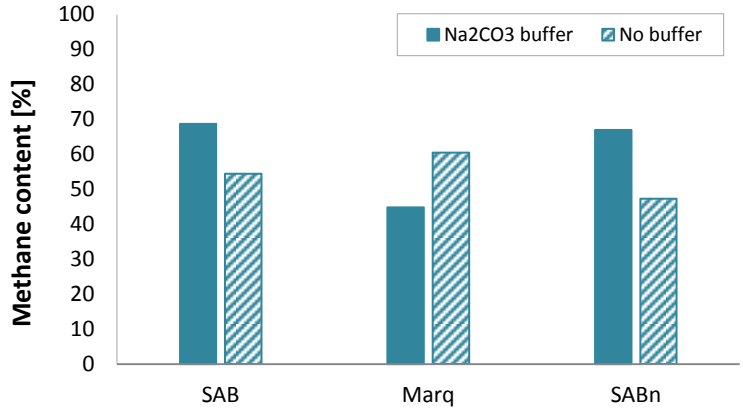


Figure 5-5: Comparison of % CH_4 obtained for buffered and non-buffered systems

For the Marquard inoculum, a higher % CH_4 was obtained for the samples that received no buffering with Na_2CO_3 in comparison to those buffered samples, confirming the suspicion that additional release of CO_2 has in fact occurred. This was not the case however, for the runs involving the SAB inoculum, where the average CH_4 percentage displayed for the buffered samples is higher than that obtained for the samples that had not been buffered.

The available data is not sufficient to draw a conclusion on, and therefore further, more controlled, experiments would be recommended to make a fair assessment on the issue at hand.

5.3 Determining projected methane produced

Although it has been shown, in the previous sections, that co-digestion results in higher yields per gram VS fed, it is not clear whether co-digestion actually improves the production yields per gram of a specific substrate. To determine this, the expected yields are calculated using weighted averages.

To illustrate this we look at the co-digestion of PM2 and AW with a ratio of 3:1 for Run 1. CH_4 yield of PM2 and AW is 231 and 355 mL/ g VS_{FED}, respectively. Using a basis of 1 g VS:

¾ X 1.0 g VS of PM2	*X 231 mL / g*	=	*173.25*
¼ X 1.0g VS of AW	*X 355 mL/ g*	=	*88.75*
		=	*262.00*

The calculated expected methane is 262 mL for a gram VS, whereas the actual methane yield obtained is 359mL, corresponding to 37% increase in the methane potential. This indicates that there is an interaction present between the substrates initiated by co-digestion. The following section shows the expected versus projected methane produced.

5.4 Mono-digestion versus co-digestion for SAB inoculum

5.4.1 Results for Run 1 with SAB inoculum

The actual methane produced for the co-digestion with PM2 is higher than that of the projected methane yields for all feeding ratios, with up to a 62% increase for the co-digestion of PM2 with AW at a 6:1 ratio. This also corresponds to the sample resulting in the highest methane yield of 402 mL/ g VS_{FED}.

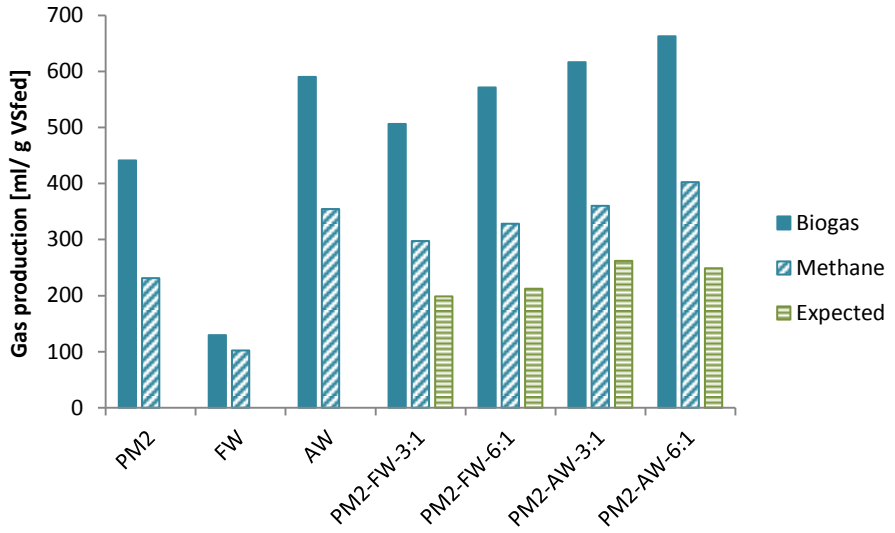


Figure 5-6: Projected versus actual yield for co-digestion of WPS [PM2]

Figure 5-7 below shows that co-digestion of PM4o and AW produced the equivalent of what was expected for both feeding ratios, within a certain degree of error. The co-digestion of PM4o and FW showed improvements in the expected methane yields of up to 60% for a feeding ratio of 3:1 which corresponds to a yield of 270 mL/g VS_{FED}.

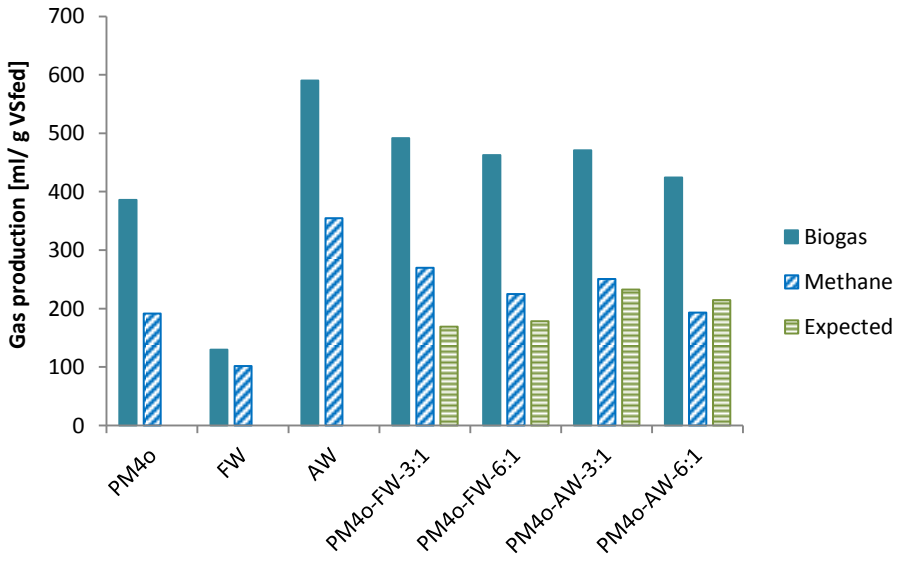


Figure 5-7: Projected versus actual yield for co-digestion of RPS [PM4o]

For the co-digestion of PM4n with AW the actual yield is equivalent to that which is expected or is lower, in the case of the 3:1 feed ratio. An improvement in the expected yield is obtained for the co-digestion of PM4n with FW for both feed ratios; with a maximum of 66% increase for a feed ratio of 3:1 resulting in a methane yield of 212 mL/g VS_{FED}.

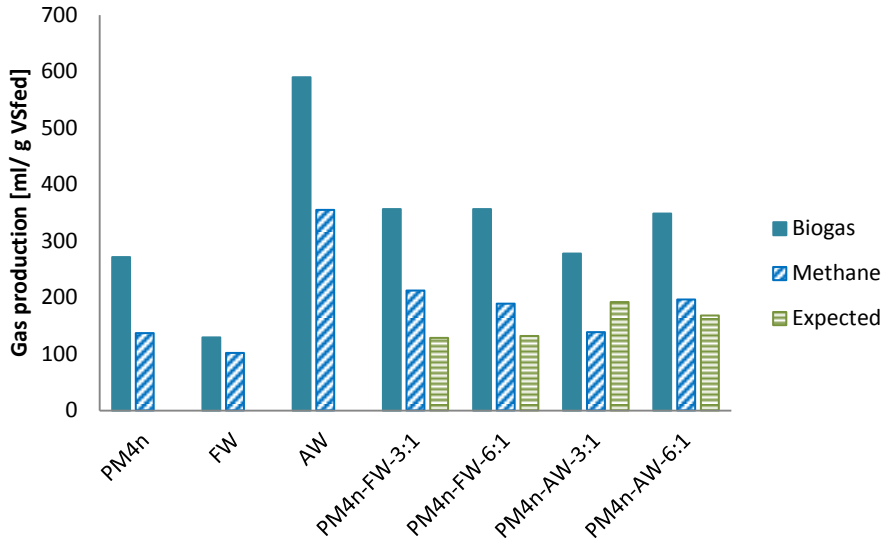


Figure 5-8: Projected versus actual yield for co-digestion of RPS [PM4n]

5.4.2 Results for Run 3 with SAB inoculum - Repeats with PM2

The repeat run for the SAB inoculum showed little or no improvement to the methane yield through co-digestion as is depicted in Figure 5-9 below.

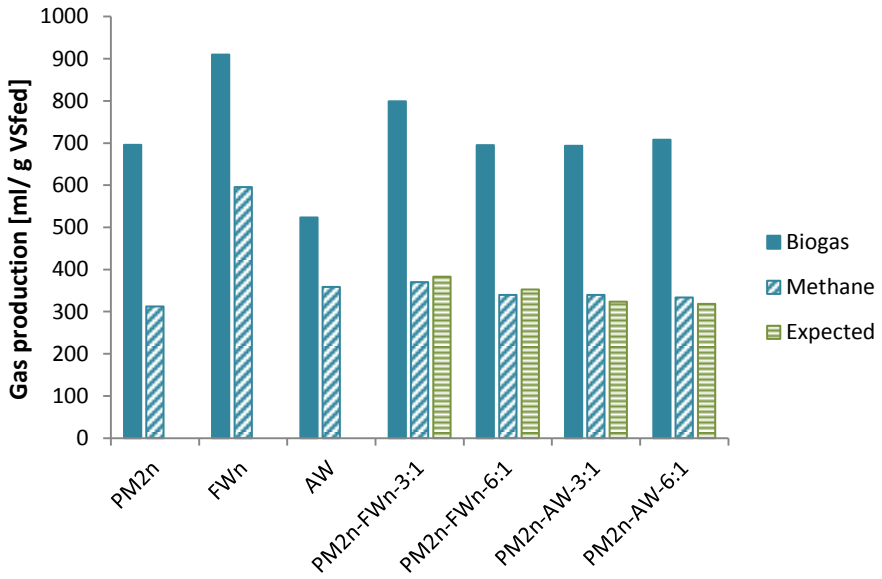


Figure 5-9: Projected versus actual yield for co-digestion of WPS [PM2n]

5.5 Mono-digestion versus co-digestion for Marquard Inoculum

As with Run 1 it was investigated whether co-digestion can improve the expected methane yield for Run 2 with the Marquard inoculum. There were some cases where this did not occur, as with PM4o and AW in Figure 5-11. Further experiments need to be performed to confirm these results.

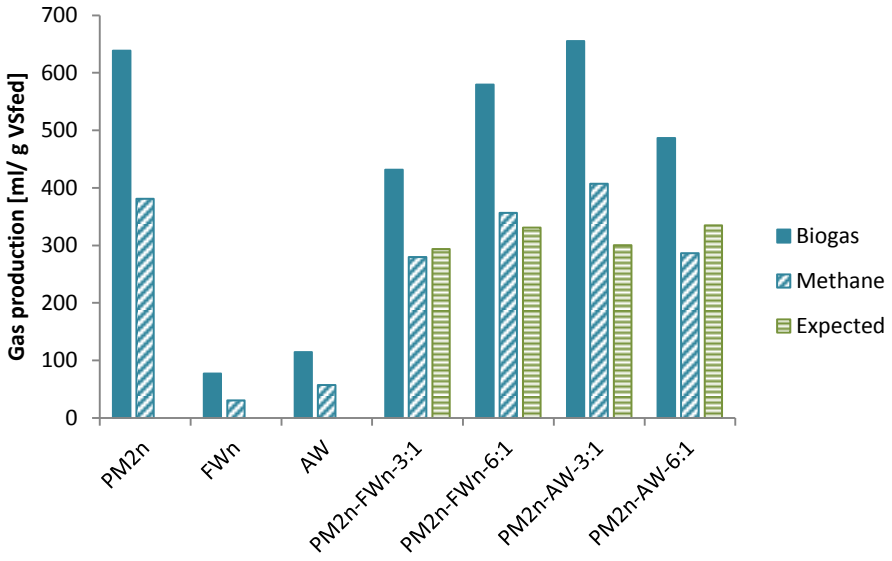


Figure 5-10: Projected versus actual yield for co-digestion of WPS [PM2n] for Run 2

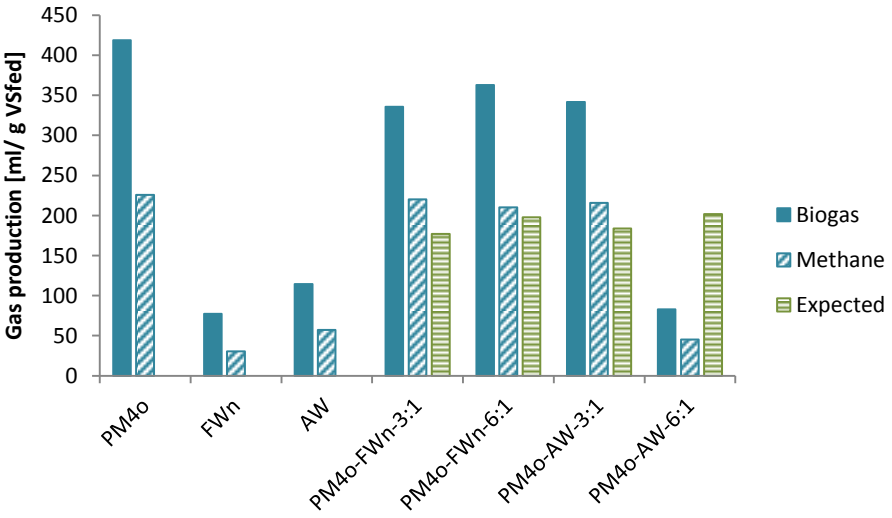


Figure 5-11: Projected versus actual yield for co-digestion of RPS [PM4o] for Run 2

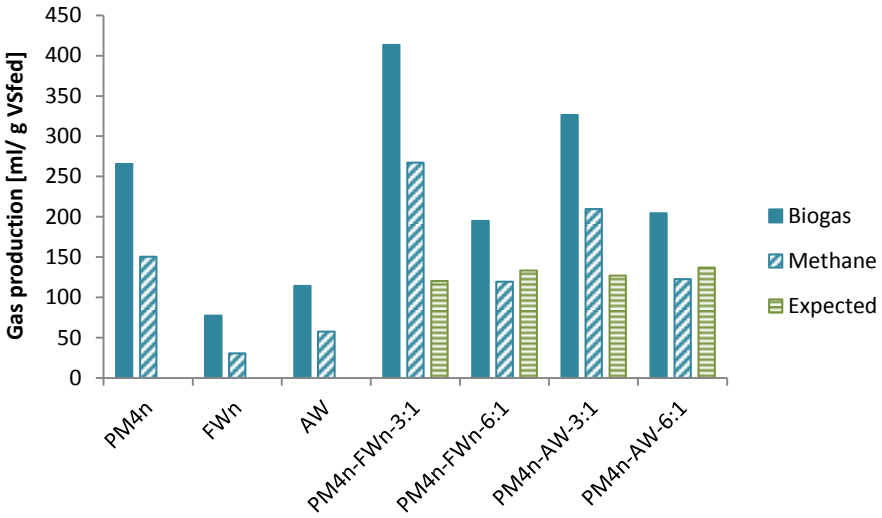


Figure 5-12: Projected versus actual yield for co-digestion of RPS [PM4n] for Run 2

In Figure 5-12 above the co-digestion of PM4n for both FW and AW in feed ratios 3:1 show an improvement to the expected methane yield; whereas that of the 6:1 ratio was equivalent to that expected.

The following section looks at the effects using different inoculums would have on the overall methane yield for specific material feeds.

5.6 SAB inoculum versus Marquard Inoculum

The following bar graphs illustrate the comparison of the methane yield obtained for each inoculum.

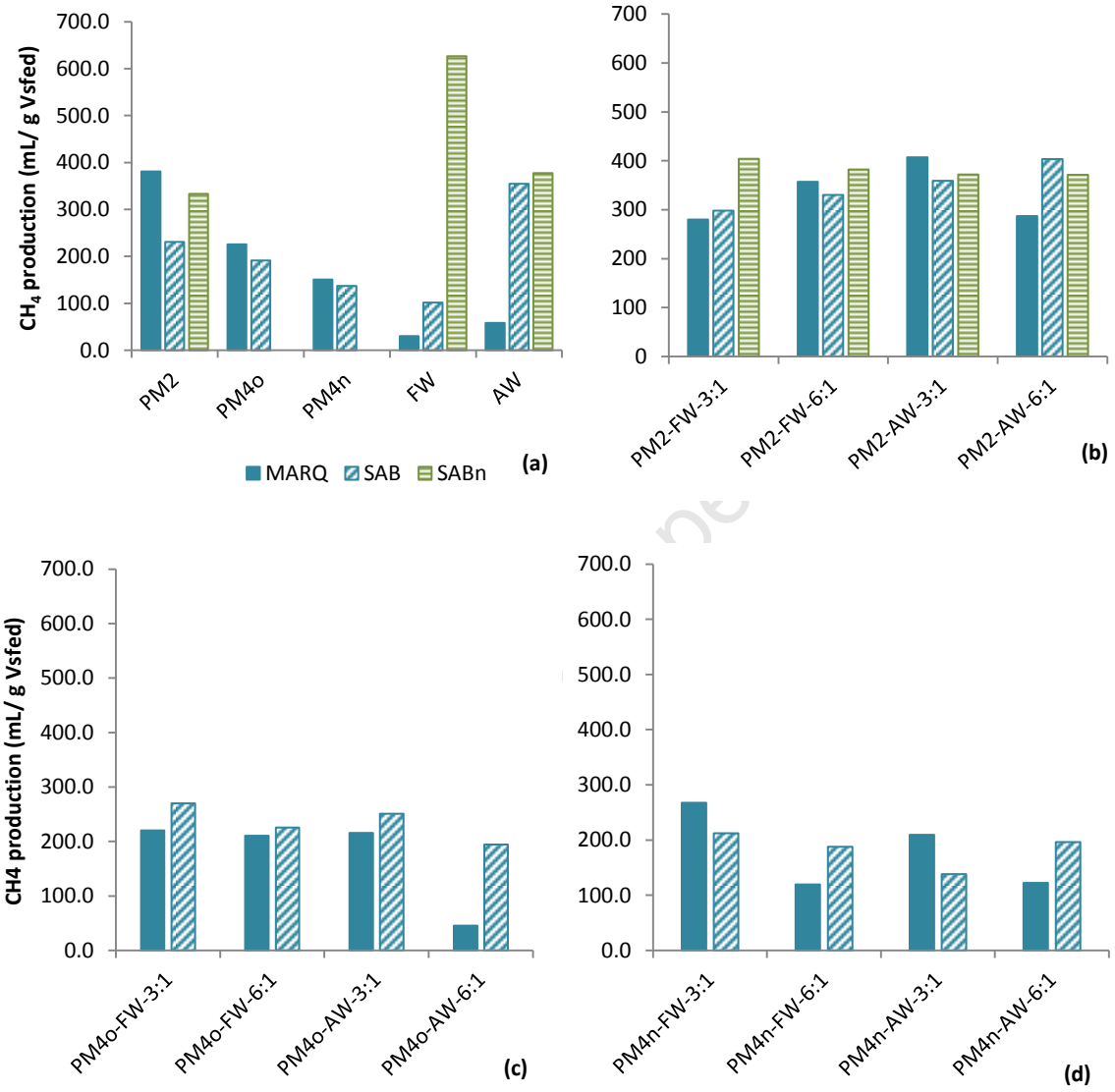


Figure 5-13: CH_4 production of SAB and Marquard inoculum: (a) mono-digestion; (b) co-digestion with PM2(n); (c) co-digestion with PM4o; and (d) co-digestion with PM4n.

Figure 5-13(a) shows that the Marquard inoculum performed better for the mono-digestion of the paper sludge, whereas the SAB inoculum performed better for the mono-digestion of the FW and significantly so for that of the AW. A possible reason for this could be the combination of the nature of the substrates and inoculum microbiology. The paper sludge consists of longer chained cellulose making it more difficult for the SAB inoculum (which is accustomed to simple carbohydrate feeds) to digest completely. The Marquard may also be ill-equipped to deal with high protein feeds such as the FW and AW.

Most of the results for the co-digestion sets were roughly on par for both Run 1 and 2, within a margin of 50mL CH_4 produced. However, this was not the case for the co-digestion of RPS with AW in 6:1 feed ratio for PM4o which was much lower for the Marquard inoculum than for the SAB inoculum. See Figure 5-13(c).

The results for PM4n in Figure 5-13(d) were more inconsistent than PM2 and PM4o. The Marquard inoculum performs better with both co-digestion with FW and AW in a 3:1 feed mix; whereas the SAB inoculum performs better with respect to the nitrogen-rich substrates in a 6:1 feed mix.

It was noted that Run 2 with Marquard inoculum started much slower than that of the SAB inoculum; the former showing first signs of production on the 4th day whereas the latter produced biogas from the 1st day (the second SAB sample produced significantly higher volumes from the 1st day of production). In light of this, it was thought useful to investigate and compare the production "dynamics" of the inoculum for a selection of runs. The cumulative biogas production curves for each inoculum were plotted alongside one another for the mono-digestion of PM2 (Figure 5-14) and AW (Figure 5-15), as well as for the co-digestion of PM2 with AW in a feeding ratio of 3:1 (Figure 5-16).

Figure 5-14 below shows a rapid rate of production over the first 20 days for the Marquard inoculum followed by slight decrease until production ceases on the 40th day, whereas the SAB inoculum experiences a halt in production from the 5th day through to the 20th day when it commences production once again. Marquard inoculum well adapted to dealing with longer chained carbohydrates, whereas SAB inoculum required a period to adapt to the feed.

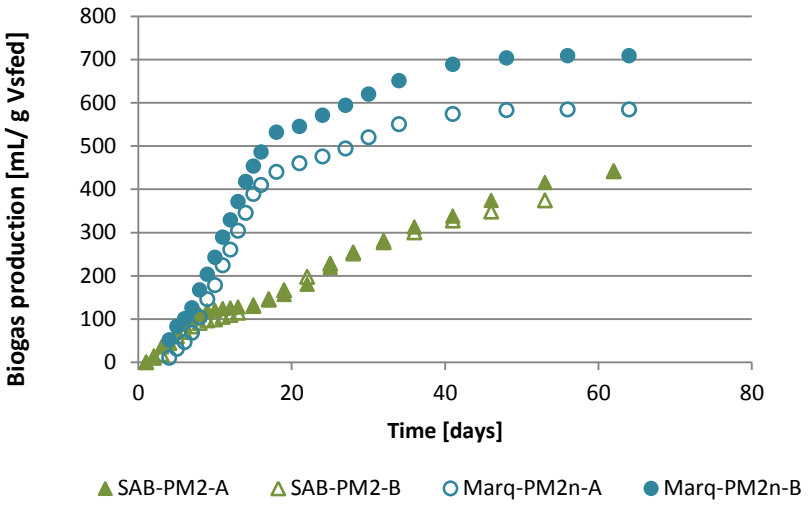


Figure 5-14: Comparison of AD dynamics of SAB and Marquard inoculum for PM2

The mono-digestion of AW with the SAB inoculum maintains a steady increase for approximately 15 days after which production slows down up until the 40th day when production comes to an end (Figure 5-15). The Marquard inoculum, on the other hand, started very slowly and ceased production by the 20th day. A possible reason for this could be that the Marquard inoculum was not well equipped to deal with the breakdown of proteins such as those found in the AW sample.

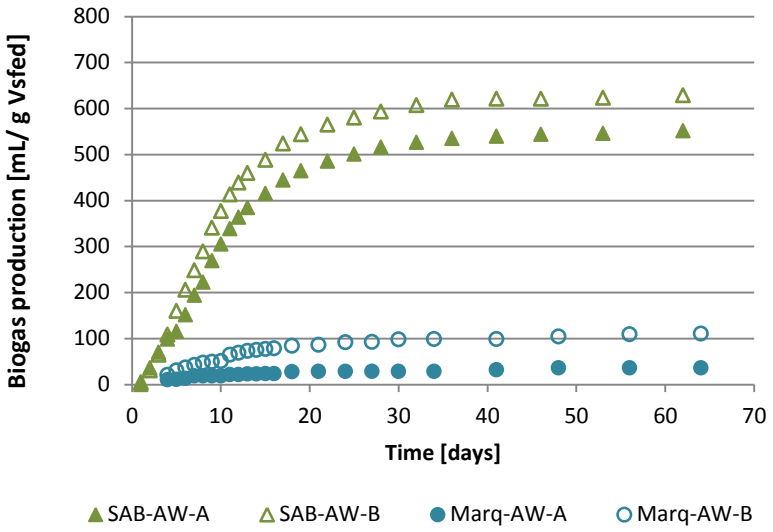


Figure 5-15: Comparison of AD dynamics of SAB and Marquard inoculum for AW

Figure 5-16 illustrates the co-digestion of PM2 and AW in a 3:1 feed ratio. Use of the Marquard inoculum resulted in a slower start off production rate than that obtained when the SAB inoculum was used. The Marquard inoculum then showed an increase in the rate of production around the 40th day which may indicate that the inoculum had adapted to the feedstock.

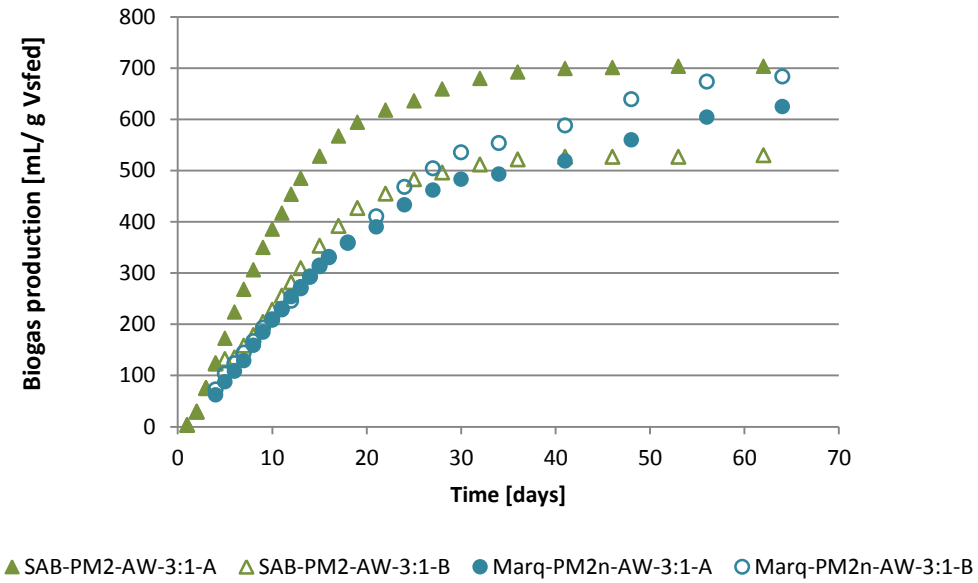


Figure 5-16: Comparison of AD dynamics of SAB and Marquard inoculum for co-digestion of AW and PM2

5.7 Energy yields for recycled paper sludge and virgin paper sludge

The inherent energy in the WPS and RPS (PM2 and PM4) was calculated using the experimental results from all the runs. A basis of 1 kg VS of untreated PS feedstock was used. It was assumed that the VS consisted solely of cellulose and the remainder is ash with zero calorific value. A lower heating value (LHV) of 34.6 MJ/m^3 CH_4 for methane was then used to determine the resulting energy yield and an LHV of 16 MJ/kg of cellulose was used to calculate the percentage energy recovery through biogas production from the mono- digestion feeding regimes (depicted in Table 5-4 below).

Table 5-4: The average percentage recovery of virgin paper sludge (PM2) and recycle paper sludge (PM4)

	PM2	PM4
Biogas production	50 - 83	30 - 50

Based on the assumptions made, PM2 derived from virgin feedstock results in a substantially higher percentage recovery of LHV than that of PM4 from recycled feedstock, depending on the inoculum used. The following sub-section presents a few concluding remarks on the experimental results.

5.8 Concluding remarks

The objectives of the BMP assays was to (i) identify which nitrogen-rich substrate would be best suited for the C:N ratio adjustment of the carbon-rich PS with respect to the biogas yields and quality thereof, and (ii) to determine what feed ratios result in the best performance. Based on the results, the following trends were observed.

I. The paper sludge derived from virgin feedstock (PM2 and PM2n in this case) performed better than the recycled paper sludge (PM4o and PM4n) for both mono-digestion and co-digestion per g VS_{FED}. However, it should be noted that the recycled paper sludge performed much faster than that derived from virgin feedstock.

II. It was shown that the co-digestion of PS with nitrogen rich substrates AW and FW can boost the expected bio-methane yields; however it should be noted that this was not always the case. The bio-methane increase, if any, was highly dependent on the choice of seed inoculum and substrate used.

III. The choice of seed inoculum did not greatly affect the gas yields for a particular co-digestion scenario; that is, the performance of a particular co-digestion scenario would be consistent for all seed inoculum used. This was not the case, however for the mono-digestion scenarios across the selected seed inoculum used. It can be concluded then that, although co-digestion may not always result in improvements with respect to the expected yields, it should aid in the stability of the system.

The selected yields obtained in the analysis of the BMP assays were obtained to address *Hypothesis 1* presented in Section 3 and to provide the data necessary for the biogas and bio-ethanol energy scenarios developed to address *Hypothesis 2*. This will be further detailed in the next section.

6 MODELLING OF RESULTS

This chapter focuses on the modelling of the two waste-derived energy products selected, investigating their production and the various options for their end use as developed in Chapter 3. An LCA approach, as prescribed by the ISO 14040, was used to assess and thus compare the impacts of these scenarios (see Figure 2-12 for the LCA framework). Based on the goal and scope defined in Chapter 3; Section 6.1 presents and discusses the compilation of the data (*LCI*) used in SimaPro to model and assess the possible systems, including a detailed description of the correlations used, the source of the particular data as well as the assumptions made. The procedure used to compile the inventory data was introduced in section3.4. Section 6.2 presents the results and analysis of the inventory of the bio-energy production options and end-use applications.

6.1 Life Cycle Inventory compilation

6.1.1 Biogas systems

The biogas options considered here are depicted in Figure 3-8 and Figure 3-11. As discussed, one of these involves the mono-digestion of WPS and the other the co-digestion of WPS with AW in a 6:1 feed ratio, based on results obtained in the previous experimental chapter. The biogas stream needs to be purified and the resulting CH_4-enriched biogas can then be used to co-generate electricity and heat. A detailed description of processes including associated limitations and assumptions made will be presented in the following sub-sections.

6.1.1.1 Biogas production process

The following diagram (Figure 6-1) illustrates the processes of the production phase considered within the system boundary. WPS, and AW in the case of the co-digestion scenario, is mixed with fresh water and added to the anaerobic digester where biogas is collected off the top and a sludge overflow is collected. Biogas produced through anaerobic digestion consists of 55 – 70 % CH_4 with the bulk of the remainder consisting of CO_2. In this case a bio-methane stream of a CH_4 purity <60% might be achieved and so it may be necessary to upgrade the biogas to 60% CH_4 through scrubbing, making it

suitable for use in a CHP unit. The sludge overflow is sent to a solid liquid separator resulting in a thickened sludge which can either be sent to landfill or alternatively it could be directed to, and a waste water stream, the latter is partially recycled. The thickened sludge can either be directed to landfill or, alternatively, it could be redirected to incineration for energy recovery. In this scenario however, the sludge to landfill option was modelled, based on current practice at Nampak Tissue where the sludge was sourced from (see Section 3.3.1 for details).

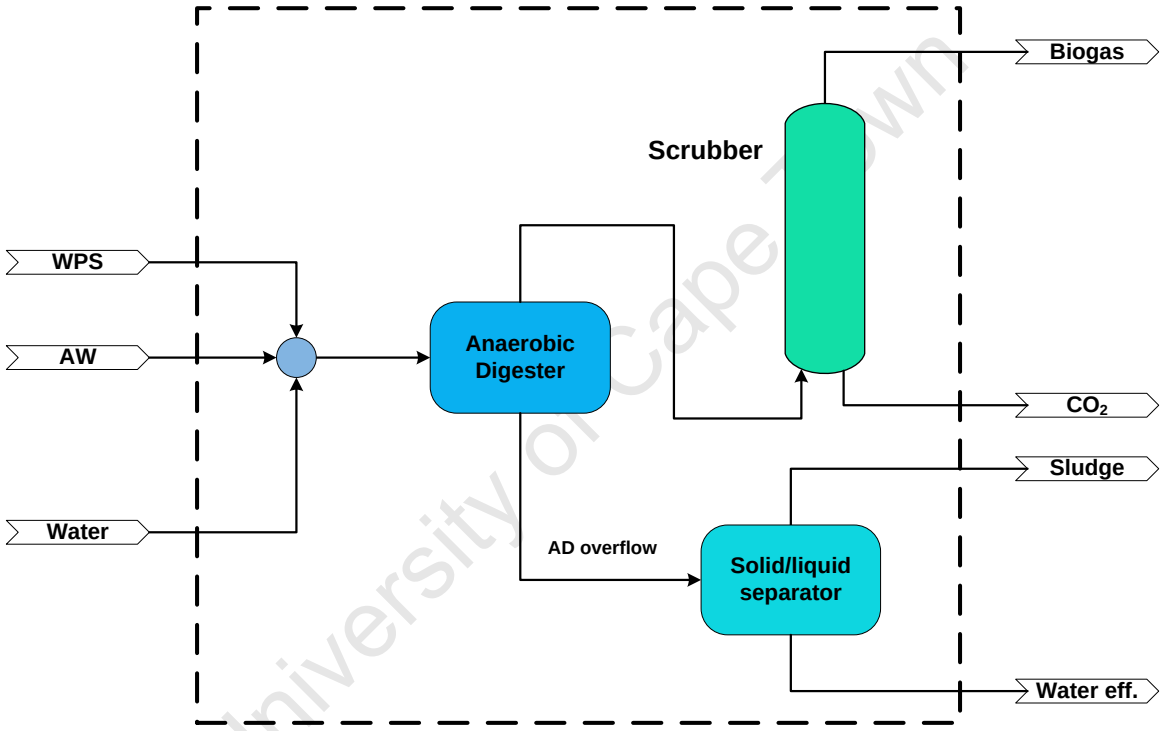


Figure 6-1: Process flow diagram of bio-methane production for LCA

6.1.1.2 Production of biogas from mono-digested WPS

The following table presents all material and energy flows associated with the production of biogas through mono-digestion of paper sludge. The material and energy balance for biogas production was performed on the basis of the biogas produced with respect to the reference flow of 67 tons of WPS per day. It was assumed that the total water fed to the reactor would be 3 times that of the WPS fed, with respect to mass. This would ensure a water content of >85% for the facilitation of digestion (Deublien and Steinhauser, 2008). This can be achieved with either pure or slightly contaminated water.

Table 6-1: Data for the production of biogas through WPS mono-digestion

Production of biogas	*1.8 x 10^5 MJ biogas (60% CH_4)*
	Materials/ fuels input
Raw WPS	67 tons
Fresh water	35 m^3
	Electricity/heat input
Electricity	7.25 x 10^3 kWh
Heat	1.14 x 10^4 MJ
	Waste products
Waste water	80 m^3
Process sludge, kg VS basis	3.4 tons
	Emissions to air
CH_4	102 kg
CO_2, biogenic	205 kg

Based on the yield obtained for PM2 in Run 1,i.e. 0.441 m^3/kg VS_{FED}, and bearing in mind that PM2 is 32.13% TS, of which 96.6% is VS; 7.7x10^3 m^3 of biogas (52% CH_4)should be produced after system losses (based on the results presented in Section 5.3). An LHV of 23 MJ/m^3 biogas (6.5 kWh/m^3 biogas) was assumed for a methane composition of 60% (Chevalier and Munier, 2005), this correlates to 1.77 x 10^5 MJ of

biogas. This corresponds to a percentage energy recovery of approximately 50% per kg VS_{FED}, as presented in Section 5.7. For the upgrading phase of the process, a 100% recovery of the total CH_4 was assumed to obtain a biogas of 60% purity. The density of biogas was calculated to be 1.2 kg/m^3 (Murphy *et al*, 2004), which corresponds to 9.3 tons of biogas. A further 3% was allocated to system losses, corresponding to approximately 102 kg CH_4, along with 205 kg of CO_2.

The overflow of the digester consists of the undigested solids and is predominantly water. The reduction of TS was measured to be 80.6% of the initial solids, resulting in 4 tons of total solids in the sludge. It was assumed that the remainder of the sludge was purely water; the water leaving the system would then be 200 m^3, which is more than that entering the system. This was accounted for by the water produced during the hydrolysis phase of anaerobic digestion. The sludge was assumed to be thickened to a TS content of 40%, of which the majority of the unreacted organic content was recovered in the sludge due to the insolubility of the cellulosic solids. A percentage (60%) of the resulting waste water stream could be recycled back to the digester and assumed not to affect the biogas yield (Deublein and Steinhauser, 2008).

The anaerobic digester was specified to run at mesophilic temperatures (37°C). Based on Chevalier and Munier (2005), 13% of the biogas energy content is used to heat the digester and 8% is used for electricity to power the ancillary equipment, such as mixers, pumps and so forth. In addition to the latter, 0.75 kWh/ m^3 CH_4-enriched biogas is required for the scrubber unit (Murphy *et al*, 2004). This falls within the ranges of 6-17% for heat requirements and 8-24% for electricity requirements for large scale biogas plants (20,000 - 60,000 tons raw material per annum) reported by Berglund and Borjesson (2006a). Therefore a total of 1.14×10^4 MJ would be used to heat the digester and 7.25×10^3 kWh for the electricity requirements.

The electricity requirements were met using the electricity generated from biogas in the CHP; however, for the biogas-based electricity scenario without heat integration (see

Figure 3-8 in Section 3.3.2.4) heat derived from coal-fired steam boilers was used. Based on Melamu *et al* (2009), the LHV for coal was assumed to be 23 MJ/kg (2.11 kWh/kg) and the steam boilers were assumed to perform at 80% efficiency, which resulted in the consumption of 0.6 tons of coal.

6.1.1.3 Production of biogas from co-digested WPS and AW

The mono-digestion and co-digestion scenarios were compared per unit volume of the anaerobic digester, the reference for the material and energy balance calculations were therefore 51.7 tons of WPS and 15.3 tons of hygienised[2] AW for the co-digestion scenario. The feed streams correlate to a feed ratio of WPS to AW of 6:1 on a VS basis. The TS content of AW is 21% of which 82.2% consists of VS. The additional water to the digester was assumed to be 3 times that of the total wet feed (on a mass basis), which consists of 55 m^3 of fresh water and a 60% recycle stream from the digester sludge treatment.

The assumptions made for mass and energy balances for the co-digestion scenarios were essentially the same as those for the mono-digestion scenarios. The following table presents the material and energy flows associated with the co-digestion process (Table 6-2 below).

[2] The thermal pre-treatment process of hygienisation is applied to reduce the pathogenic micro-organisms in the feedstock.

Table 6-2: Data for the production of biogas through co-digestion of WPS and AW

Production of biogas	*2.4 x 10^5 MJ biogas (60% CH_4)*
	Materials/ fuels input
Raw WPS	52 tons
Hygienised AW	15 tons
Fresh water	39 m^3
	Electricity/heat input
Electricity	9.81 x 10^3 kWh
Heat	1.55 x 10^4 MJ
	Waste products
Waste water	77 m^3
Process sludge, kg VS basis	4.9 tons
	Emissions to air
CH_4	138kg
CO_2, biogenic	277 kg

The yield for the co-digestion of PM2 and AW was determined to be 0.663 m^3/kg VS_{FED}; resulting in 1.04x 10^4 m^3 of biogas of 52% CH_4 after system losses, which corresponds to 2.4 x 10^5 MJ of biogas. Effects on the heat input due to variations to hygienisation requirements for different raw materials are assumed negligible as the heat can easily be recovered and used for additional heating for the digester (Berglund and Borjesson, 2006a). Therefore, a total of 1.55 x 10^4MJ was used to heat the digester and 9.81 x 10^3kWh for the electricity requirements. As with the mono-digestion options, the electricity requirements of the production phase was accounted for by the electricity generated from the biogas-based CHP and the heat used for the scenario without heat integration (see Figure 3-11 in Section 3.3.2.4) was coal-based. Therefore, the coal used for this heating purposes amounted to 0.8 tons, which is 0.2 tons more than that required for the mono-digestion scenario.

Losses of methane and CO_2 to the atmosphere correspond to 3% of the total produced, resulting in 138 kg CH_4 and 277 kg, respectively. The TS reduction over the digester was found to be 60.5%, resulting in 15 tons of sludge containing 40% TS and a waste water stream of 77 m^3. This sludge is sent to landfill, which will be discussed later in detail. The end use emissions from the use of biogas for the co-generation of heat and power (CHP) will be discussed in the next section.

6.1.1.4 Use of biogas for power generation

For the power generation scenario involving biogas, the biogas (60% CH_4) is combusted in a co-generation unit which produces electricity and converts the energy of the flue gases to generate steam for the provision of process heat. The data depicted in Table 6--4 was obtained for the combustion of 1 m^3 of biogas with the following properties.

Table 6-3: Biogas from AD composition on a volume basis

Component	*Vol. %*
CH_4	60
CO_2	37
N_2	1.5
H_2	0.5
O_2	0.5
H_2S	30 ppm

An LHV of 23 MJ/m^3 of biogas was assumed; with the result of 23 MJ of energy available from 1 m^3 of biogas. A global efficiency of 87% was assumed (Deublein and Steinhauser, 2008); 50% thermal energy and the remaining 37% electrical energy. This resulted in 2.4 kWh of electricity and 11.5 MJ of useful heat.

Table 6-4: Data for the combustion of 1 m^3 biogas for co-generation of electricity and heat (*CHP*)

Production of 2.4 kWh of electricity	
	Materials/fuels input
Biogas (60% CH_4)	23 MJ
	Emissions to air
Useful heat	11.5 MJ
CO_2	207 g
NO_X	400 mg
CO	500 mg
VOC	400 mg
SO_2	9.4 mg

To calculate the emissions, only methane was considered to burn and produce energy, correlating with the following stoichiometric equation:

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$$

An air to fuel ratio of 1.4, on a molar basis was assumed, resulting in 1.68 m^3 of O_2 for 1 m^3 of biogas. Therefore 8.4 m^3 of air was required, and if no volume variation occurs, this would result in an exhaust gas of 9.4 m^3, with the composition depicted in Table 6-4 under the emissions to air (Chevalier, 2005).

6.1.2 Ethanol systems

The bio-ethanol options considered are depicted in Figure 3-5, Figure 3-6 and Figure 3-7. These involve the production of bio-ethanol for power generation or, through subsequent purification, a transport fuel for use in a flexi-fuel vehicle (FFV). The production process and subsequent end-use processes will be described in further detail in the subsequent sections, including the associated assumptions made.

6.1.2.1 Ethanol production process

The diagram below (Figure 6-2) shows the processes considered for the production phase of the ethanol. As with the biogas system, the WPS is diluted and then fed to the SSF unit. Here, CO_2 is captured and the effluent containing dilute ethanol and other impurities is distilled, resulting in an ethanol–rich stream of ~95% purity suitable to be used for electricity generation. The bottoms, containing unreacted solids and water, is sent to a solid-liquid separator where it is thickened and sent to landfill. Further dehydration is necessary to achieve a 99.6% ethanol-rich fuel for use in vehicles.

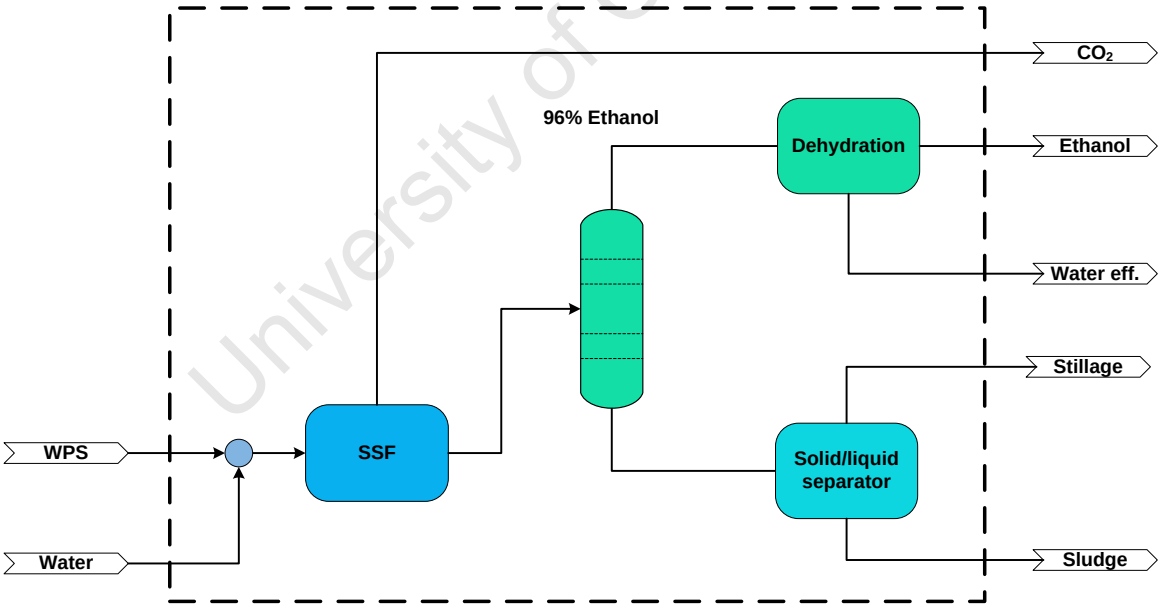


Figure 6-2: Process flow diagram of bio-ethanol production for LCA

The data used to model the production of ethanol was obtained from various sources and will be detailed in further descriptions of the calculations. A reference flow of 67 tons of

PM2 was used for the material and energy balance for ethanol production as well. It was assumed that 2 times the amount of water would be mixed with the raw WPS, to ensure an insoluble solid concentration below 5% to facilitate the simultaneous saccharification and fermentation of the WPS.

Although a solids concentration of 5% was used here, recent studies have shown that waste paper sludge can be fermented at solids concentrations of up to 20% (Fan and Lynd, 2007) resulting in an increase in ethanol concentration as well as a decrease in the energy requirements of the distillation column. On further calculation ~20% increase in ethanol concentration was achieved and ~10 decrease in the overall energy requirements resulted from the increase in solids concentration of the feed. However, based on the negligible effects on the final environmental impact results comparison, the following calculations involving ethanol production were calculated at a solids concentration of 5% in the feed.

The yield of 0.184 kg EtOH/kg dry RPS was obtained from Lark *et al* (1996), presented in Table 2-3 in Section 2.6 of the literature review. The study involved the testing of the production of ethanol from recycled paper sludge through SSF for paper sludge (PS) with 50% cellulose composition on a dry mass basis. This correlates to 0.363 kg EtOH/kg VS_{FED} based on the assumption that all the VS of the WPS is equivalent to cellulose. Therefore, 67 tons of PM2 generates 7.4 tons of ethanol. Furthermore, for every two mols of ethanol produced, two mols of CO_2 are produced, resulting in a total of 7.0 tons of CO_2. As with the biogas options, the unreacted 4.5 tons of the TS was removed through filtration of the SSF effluent, which resulted in 11.2 tons of sludge consisting of 40% solids, 3% ethanol and the remainder water. The filtrate, which consists of 5% ethanol, is fed into a distillation column where 96% EtOH is recovered to produce a 95% pure EtOH product stream of 7.4 tons, which corresponds to 1.9×10^5 MJ of inherent energy. This correlates to an energy recovery of 52% per kg VS_{FED}, as calculated in Section 2.6. The distillate consists of 99.8% water and 0.2% EtOH; of which 40% is recycled back to the SSF unit without any adverse effects on the EtOH yield (Wingren *et al*, 2003).

For the use of ethanol for a flexi-fuel vehicle, the EtOH product stream is further dehydrated to 99.6% EtOH and the remainder water. A 100% recovery of ethanol was assumed, resulting in a product stream of 7.1 tons, which corresponds to 1.9×10^5 MJ of inherent energy based on an LHV of 26.7 MJ/kg.

Kim and Dale (2005) reported a case for dry milling involving 5 phases and their percentage contribution to the overall energy requirement of 17.1 MJ/ kg EtOH produced. It was further reported that the thermal requirements contributed to 85% of the total energy requirements and electrical requirements contributed the remaining 15%. No milling or DDGS was necessary for the paper sludge to ethanol process; the weighted average was calculated to be 15.3 MJ/kg EtOH. It was further assumed that the energy requirement for the SSF unit would simply be the sum of the saccharification and fermentation steps, which is an over estimation based on various studies investigating the two system approaches (Lynd *et al*, 1996). On the other hand, the contribution of the distillation column would be an under estimation due to the low concentrations of EtOH from the SSF unit (Lynd *et al*, 1996). It was thus assumed that overall there would be no change in the energy requirement.

Table 6-5: Data for the production of ethanol

Production of ethanol	*1.89 x 10^5 MJ (95% EtOH)*	*1.89 x 10^5 MJ (99.6% EtOH)*
	Materials/ fuels input	
Raw WPS	67 tons	67 tons
Fresh water	46 m^3	46 m^3
	Electricity/heat input	
Electricity	4.9 x 10^3 kWh	5.1 x 10^3 kWh
Heat	1.01 x 10^5 MJ	1.01 x 10^5 MJ
	Waste products	
Waste water	85 m^3	85 m^3
Ethanol	176 kg	176 kg
Process sludge, kg VS basis	3.7 tons	3.7 tons
	Emissions to air	
CO_2 biogenic	217 kg	217 kg

Therefore, based on the production of 7.75 tons of EtOH, 1.01 x 10^5 MJ of energy would be necessary for the thermal process requirements and 4.9 x10^3 kWh for the electric requirements. As with the biogas scenarios, the bio-ethanol based electricity was used for the electricity requirements of the production phase. However, for the thermal requirements, a coal-fired boiler was used (η_{elec} = 0.8), which corresponds to a total of 5.5 tons of coal.

For bio-ethanol fuel production further purification of the ethanol would be done using a molecular sieve, which was assumed to incur an additional energy requirement of ~1% of that required for distillation (Madson, 1995). This corresponds to a total of 1.014 x 10^5 MJ for the thermal requirements and 5.1 x 10^3 kWh for the electricity requirements. As no electricity was generated to integrate into the system, all electricity and thermal requirements were satisfied using the coal-based alternatives, which resulted in a coal usage of 7.9 tons.

6.1.2.2 Use of ethanol for power generation

The power generation from ethanol scenario involves the combustion of ethanol in a gas turbine (η_{elec} = 0.37) to produce electricity. The combustion of 1 kWh of ethanol in a 35% efficient gas turbine, results in the following emissions (Strachen and Farrel, 2006).

Table 6-6: Data for the combustion of ethanol for electricity generation

Production of 1.24 MJ electricity	
	Materials/fuels input
EtOH (95% purity)	3.54 MJ
	Emissions to air
CO_2	300 g
NO_X	290 mg
CO	420 mg
PM_{10}	41 mg

For the co-generation scenario a global efficiency of 87% was assumed, with 50% thermal energy. An LHV of 26.7 MJ/kg of ethanol was assumed; which resulted in 2.03 x 10^4 kWh of electricity and 9.73 x 10^4 MJ of useful heat.

6.1.2.3 Use of ethanol for combustion in vehicles

The GREET model was used to simulate the emissions of the E100 fuel mix for a flexi-fuel passenger vehicle (E-FFV) in the passenger vehicle sub-class. It was also used to determine the mileage achievable per MJ of inherent energy and the emissions associated with this scenario (Table 6-8).

Table 6-7: Data for the combustion of ethanol in a flexi-fuel vehicle (E-FFV) for 1 km driven

Production of 1 km driven	*E-FFV*
	Materials/ fuels input
EtOH (99.6 % CH_4)	3.18 MJ
	Emissions to air
CO_2	226 g
CH_4	9 mg
N_2O	7 mg
VOC	103 mg
CO	2.296 g
NO_X	79 mg
PM_{10}	18 mg
$PM_{2.5}$	9 mg
SO_X	1 mg

6.1.3 Waste treatment scenarios

A sludge waste stream is produced through the production of the bio-energies. A waste scenario was modelled to simulate the emissions associated with the disposal of the sludge in landfill sites. Based on Murphy *et al* (2004) a maximum destruction of volatiles of 65% was assumed as well as a production a 0.441 m^3 of landfill gas per kg of volatile solids as was achieved for the mono-digestion of WPS in the BMP assays.

Table 6-8: Emissions associated with landfill of waste paper sludge

0.441 m^3 of landfill gas	
	Materials/ fuels input
Process sludge, kg VS basis	1 kg
	Emissions to air
CH_4	0.22 m^3
CO_2	0.13 m^3
CO	0.001 m^3
N_2	0.07 m^3
O_2	0.01 m^3
H_2S	3500 mg

The composition of the landfill gas was calculated as the average of range of volumetric compositions given for each component in Deublein and Steinhauser (2008); it was assumed the trace volumes of NH_3 were negligible. It was further assumed, for the sake of simplicity, that the variations to the composition of the landfill gas due to the source of the VS were negligible.

6.1.4 Fossil energy carriers

As discussed prior to this, the production processes of the fossil energy carriers used to fuel the production processes, or replaced by the energy products, are included in the system boundary; these are:

i. Coal-based electricity production
ii. Coal-based steam generation for heating
iii. Conventional gasoline for use as vehicle fuel

An LHV of coal of 23 MJ/kg (2.11 kWh/kg) was used, and the corresponding efficiencies thereof for electricity generation and heat generation was assumed to be 35% and 80%, respectively. The emissions associated with electricity generation were obtained from Eskom's Annual Report (2006). An existing process of coal-based heat generation in

the BUWAL 250 process from SimaPro was modified to model the 80% efficiency and emissions associated with the process of steam generation for heating purposes in a South African context.

6.1.4.1 Use of conventional gasoline for system expansion

Further details on the implementation of system expansion for the bio-ethanol scenarios, and thus the application of the conventional gasoline, will be discussed in subsequent sections. The data used for the production of gasoline was also obtained through slight modifications made to an existing process in the BUWAL 250 process from SimaPro database. Changes were made to the emissions and the coal source was replaced with that of coal mined in South Africa.

Table 6-9: Data for the combustion of conventional gasoline in a passenger car (PC)

Production of 1 km driven	*PC*
	Materials/ fuels input
Conventional gasoline	3.18 MJ
	Emissions to air
CO_2	231 g
CH_4	9 mg
N_2O	7 mg
VOC	108 mg
CO	2.296 g
NO_X	79 mg
PM_{10}	18 mg
$PM_{2.5}$	9 mg
SO_X	4 mg

The LHV of the gasoline was assumed to be 43.45 MJ/ kg gasoline. The data used to model the combustion of conventional gasoline as fuel in the two vehicle classes selected were calculated using the GREET model (Table 6-9).

Using the compiled inventory data, the various bio-energy scenarios were modelled and assessed in SimaPro using the CML 2 Baseline 2000 V2.03 method as described in Chapter 3. The results thereof will be discussed in the subsequent section.

6.2 Life cycle inventory analysis

The scenarios were modelled on a basis of 67 tons of WPS for SYSTEM 1, and 52 tons of WPS and 15 tons of AW in the case of the co-digestion scenarios. This section presents the inventory results of these scenarios, which will be assessed on:

(i) the energy yield ratio, which is essentially the ratio of the energy input to the inherent energy of the bio-energy produced; and
(ii) The percentage reduction of VS fed to the system.

This was performed at the LCI phase, further discussions on the environmental impacts of the production processes will be presented in Sections 7.1 and 7.2 where the end-use applications are assessed. The scenarios are presented in two *schemes*, the first represents those scenarios developed to test *hypothesis 1* and the second represents the scenarios compared to test *hypothesis 2*.

The system boundary included in the material and energy balance was the bio-energy conversion technology, solid-liquid separator, landfill treatment of the process sludge and upgrading processes. In addition to this, the mono-digestion options were expanded further to include the landfilling of AW so as to make a fair comparison across performance categories when including the co-digestion options.

6.2.1 Bio-energy production options for SYSTEM 1

The following table presents the major flows associated with the bio-energy production phase of the selected scenarios for SYSTEM 1 which was described in the Goal and Scope of the study (see Section 3.3.1), with respect to the selected reference flow of 67 tons of WPS. The major energy flows, presented here in Table 6-11, are the energy requirements for the production phase as well the bio-energy potential. The material flows considered here is the water added and the process sludge generated on a kg VS basis.

Table 6-10: Major flows of bio-energy production phase for scenarios of SYSTEM 1

		MBE	MBE-HI	EE	EE-HI	E-FFV
Process sludge	***kg***	1.05E+04	1.05E+04	1.12E+04	1.12E+04	1.12E+04
	kg VS	3.45E+03	3.45E+03	3.74E+03	3.74E+03	3.74E+03
Overall VS reduction	***%***	83	83	82	82	82
Coal-based energy added for production of bio-energy	***kWh***	0	0	0	0	5.06E+03
	MJ	1.14E+04	0	1.01E+05	3.527E+03	1.01E+05
Coal added	***kg***	620	**0**	5500	192	**7900**
Inherent energy in coal	***MJ***	1.43E+04	0	1.21E+05	4.41E+03	1.82E+05
Ethanol produced	***kg***	-	-	7.75E+03	7.75E+03	7.39E+03
Inherent energy in ethanol	***MJ***	-	-	1.95E+05	1.95E+05	1.97E+05
Biogas produced	***m^3***	7.71E+03	7.70E+03	-	-	-
Inherent energy in biogas	***MJ***	1.77E+05	1.77E+05	-	-	-
Energy performance ratio	***MJ/ MJ***	0.08	**0**	0.62	0.02	**0.92**
Net energy yield	***MJ***	1.63E+05	**1.77E+05**	7.36E+04	1.90E+05	**1.54E+04**

Of the ethanol-based scenarios, the power generation options (EE and EE-HI) perform better with respect to the fossil energy input per unit bio-ethanol produced as well as the net energy yield, as expected due to the reduction in fossil energy input through the integration of ethanol-based electricity for both scenarios (EE and EE-HI) and heat for one scenario (EE-HI).

Overall, the biogas scenario with heat integration (MBE-HI) performs significantly better in comparison to all ethanol scenarios (EE and EE-HI) with respect to the energy performance. The ethanol scenario with heat integration performs second best, with a higher net energy yield. The thermal requirements of the ethanol scenarios far exceed those of the biogas alternatives. On this note, the integration of bio-energy based heat into the production phase results in an improvement in performance for both the ethanol and bio-methane options. Heat integration results in coal usage reductions of 0.6 tons for the bio-methane options and 0.5 tons for the bio-ethanol options.

The percentage VS reduction was calculated on the basis of 20.8 tons of VS fed to the system, which corresponds to the volatile solids of 67 tons of WPS. Both the biogas and ethanol scenario options achieve substantial VS reductions of 83% and 82%, respectively.

The following section presents the major flows of the production options for the second system, which will be described further as well.

6.2.2 Bio-energy production options for SYSTEM 2

The second system addresses *Hypothesis 2*, which compares the effects of mono-digestion of 67 tons of WPS (MBE and MBE-HI) to the co-digestion of WPS with AW in a feed ratio of 6:1 (CBE and CBE-HI) per unit digester volume. This corresponds to approximately 52 tons of WPS and 15 tons of AW. The same material and energy flows as those presented for *SYSTEM 1* were considered here.

Table 6-11: Major flows of bio-energy production phase for selected scenarios for SYSTEM2

		MBE	MBE-HI	CBE	CBE-HI
Process sludge	***kg***	1.05E+04	1.05E+04	1.49E+04	1.49E+04
	kg VS	3.45E+03	3.45E+03	4.87E+03	4.87E+03
Overall VS reduction	***%***	83	83	74	74
Coal-based energy added for production of bio-energy	***kWh***	-	-	-	-
	MJ	1.14E+04	0	1.55E+04	0
Coal added	***kg***	620	**0**	**841**	0
Inherent energy in coal	***MJ***	1.43E+04	0	1.93E+04	0
Biogas produced	***m^3***	7.71E+03	7.70E+03	1.04E+04	1.04E+04
Inherent energy in biogas	***MJ***	1.77E+05	1.77E+05	2.40E+05	2.40E+05
Energy yield ratio	***MJ/ MJ***	0.08	**0**	0.08	**0**
Net energy yield	***MJ***	**1.63E+05**	1.77E+05	2.21E+05	**2.40E+05**

The energy yield ratio is the fossil energy input required per MJ bio-methane produced. These were the same for the scenarios MBE and CBE and also for MBE-HI and CBE-HI as the same correlation of energy input requirements to energy output was used for both the mono-digestion and co-digestion scenarios. With respect to the net energy yield, however, the co-digestion scenarios dominate, demonstrating the effects of the improved CH_4 yields obtained for the co-digestion options.

The integration of heat for both mono-digestion and co-digestion displayed marked improvements in both energy performance ratio as well as the net energy yield due to the large coal savings; 0.6 tons for mono-digestion and 0.8 tons for co-digestion. Overall the co-digestion scenario with heat integration (CBE-HI) performed the best. The mono-digestion scenario generates less sludge, with respect to kg VS, than the co-digestion scenario.

The following section presents the major flows associated with the end-use applications of the various scenarios within *SYSTEM 1* and *SYSTEM 2*.

6.2.3 Bio-energy power generation and vehicle scenarios

In this section, the production phases of the scenarios discussed were expanded to include the various end-use applications selected and the performance thereof is considered here. The major flows presented in the following table are the coal usage and the electricity generated (kWh) or mileage achieved (km driven).

As illustrated in the previous section, the ethanol-based transport (E-FFV) option displayed the highest coal usage for the process electricity and heat requirements, followed by the ethanol-based electricity option without heat integration (EE) and the biogas option without heat integration (MBE). The bio-energy scenarios with heat integration (EE-HI and MBE-HI) performed better than their counterparts. At this point, all the scenarios cannot be compared any further due to the differing functional outputs.

Table 6-12: Major flows associated with the end-use applications of SYSTEM 1

		MBE	MBE-HI	EE	EE-HI	E-FFV
Coal added	***kg***	620	**0**	5500	192	**7900**
Inherent energy in coal	***MJ***	1.43E+04	0	1.21E+05	4.41E+03	1.82E+05
Electricity from WPS	***kWh***	**1.13E+04**	**1.13E+04**	**1.54E+04**	**1.54E+04**	-
	MJ	4.00E+04	4.00E+04	5.45E+04	5.45E+04	-
Mileage achieved from WPS	***km***	-	-	-	-	6.21E+04
Energy performance ratio	***MJ/ MJ***	0.36	**0**	**2.22**	0.08	-
	MJ/ km	-	-	-	-	2.9

So if we only consider the power generation scenarios, the ethanol scenarios generate the highest electricity output and the biogas options generate the least. To properly assess the performance of the systems, the ratio of the fossil energy input required per MJ electricity generated is calculated. Based on these energy ratios, it is clear that the biogas option with heat integration dominates as it requires no fossil energy input.

The following table below (Table 6-13) presents the major flows of the end-use applications of the scenarios of *SYSTEM 2*, and the performance thereof. As expected, the co-digestion scenarios (CBE and CBE-HI) generated more electricity based on the higher yield obtained in the BMP experimental analysis in Chapter 5.

An improved energy performance is displayed with the integration of the useful heat generated in the CHP. As expected, the energy performance ratio for the scenarios MBE and CBE are the same, as are the scenarios MBE-HI and CBE-HI. This essentially means that the fossil energy input per MJ electricity generated is consistent, however a comparison needs to be made on the basis of the selected reference flows.

Table 6-13: The major flows associated with the power generation scenarios of SYSTEM 2

		MBE	MBE-HI	CBE	CBE-HI
Coal added	***kg***	620	**0**	**841**	0
Inherent energy in coal	***MJ***	1.43E+04	0	1.93E+04	0
Electricity from WPS	***kWh***	**1.13E+04**	**1.13E+04**	**1.52E+04**	**1.52E+04**
	MJ	4.00E+04	4.00E+04	5.38E+04	5.38E+04
Energy performance ratio	***MJ/ MJ***	**0.36**	**0**	**0.36**	**0**

To effectively evaluate and compare the overall performance of the end-use applications in question on the basis of the selected reference flow (67 tons WPS) for each system developed, it was necessary to expand the system. Therefore, the process of system expansion was implemented, as described in Section 3.4. The following Chapter presents the results thereof along with a comparative interpretation.

7 COMPARISON AND INTERPRETATION

This chapter details the procedure followed to expand the two bio-energy systems (SYSTEM 1 and SYSTEM 2) that have been developed to test the hypotheses put forward (Section 7.1 and Section 7.2) and presents the impact assessment results thereof. This is followed by a summary of the interpretation of the results in Section 7.3.

7.1 Comparison of expanded bio-energy scenarios for SYSTEM 1

The power generation and transport fuel scenario options were expanded through the addition of the traditionally used coal-based electricity and gasoline vehicle fuel so as to generate a single output. Based on the maximum functional outputs for the scenarios, a combined system functional output of 6.21 x 10^4 km driven and 1.54 x 10^4 kWh (5.45 x 10^5 MJ) of electricity was selected (Figure 7-1).

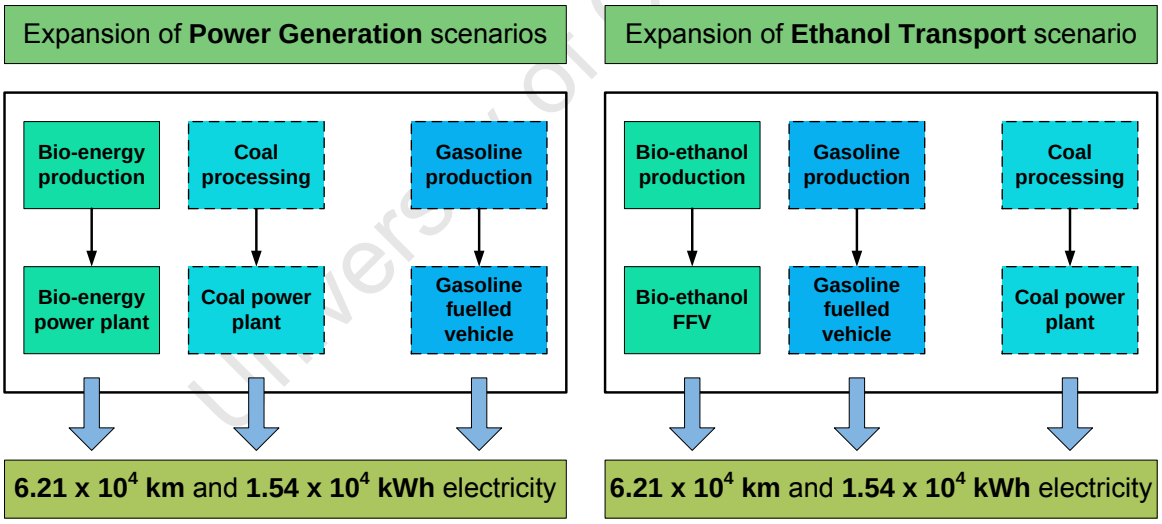


Figure 7-1: Schematic of application of system expansion to achieve overall functional output for SYSTEM 1

The following section describes the procedure followed to expand the system in question and presents major flows and a discussion thereof.

7.1.1 Procedure of system expansion for SYSTEM1

A graph of the major fossil energy flows depicting the contribution of the different energy processes to the overall fossil energy consumption of each scenario to achieve the selected combined functional output is presented below (Figure 7-5). A summary table is presented in Appendix 9.4. These expanded scenarios were modelled and compared in SimaPro using the CML 2 baseline 2000 V2.03 method. The LCA results of these expanded systems are presented in the subsequent section.

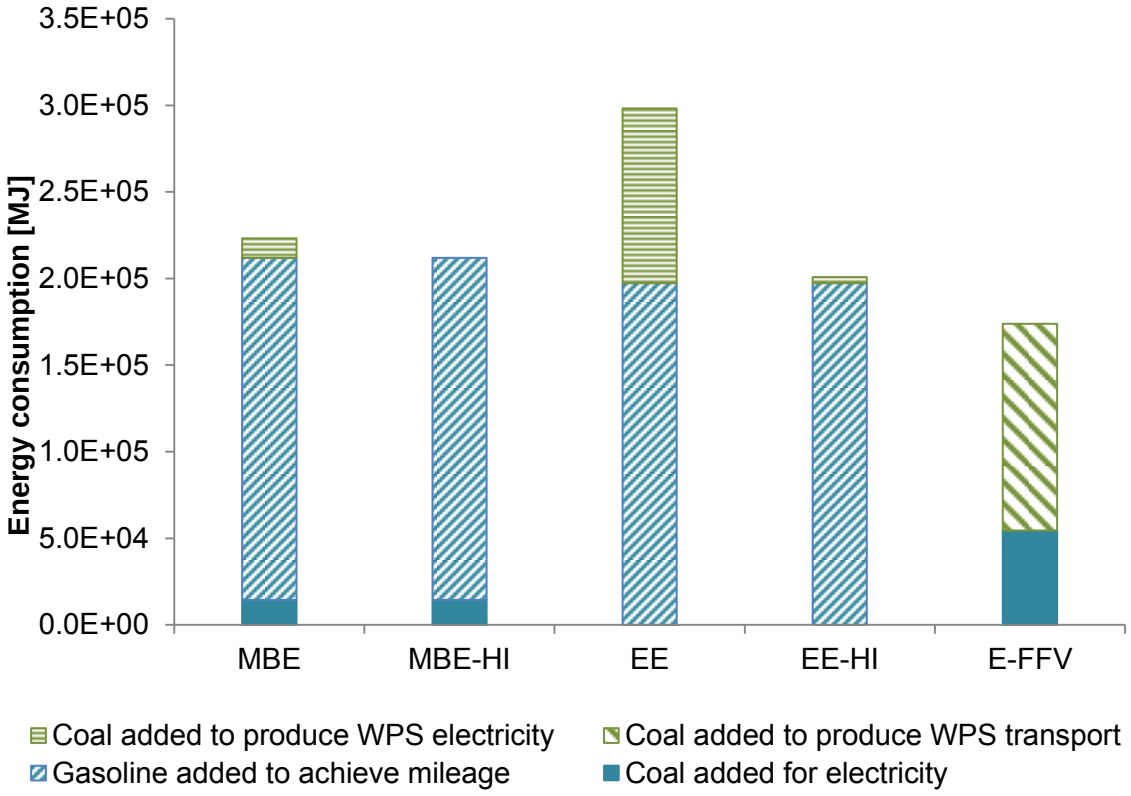


Figure 7-2: Overall consumption of fossil energy to achieve an overall functional output of 1.54 x 10^4 kWh electricity and 6.21 x 10^4 km driven for SYSTEM 1

With respect to the overall fossil energy consumption of the expanded systems (Figure 7-5); it should be noted that all the power generation scenarios consumed the same amount of gasoline. The transport scenario E-FFV displayed the lowest fossil consumption of only 1.74 x 10^5 MJ.

The EtOH electricity scenario (EE) exhibited the highest fossil-energy consumption (2.98 x 10^5 MJ) due to the high coal requirements for EtOH production. The integration of heat (EE-HI) showed substantial improvement with respect to the overall fossil energy input. The biogas scenarios were similar to that of the EE-HI scenario; with the heat integration scenario (MBE-HI) being only marginally better than that without heat integration (MBE). The following section presents the impact assessment results.

7.1.2 Impact assessment results for expanded systems

Based on the data obtained from the inventory analysis, the various scenarios were modelled in SimaPro and assessed using the CML 2 baseline 2000 V2.03 method. The following chart (Figure 7-3) presents the comparison of the scenarios considered with respect to the selected impact categories.

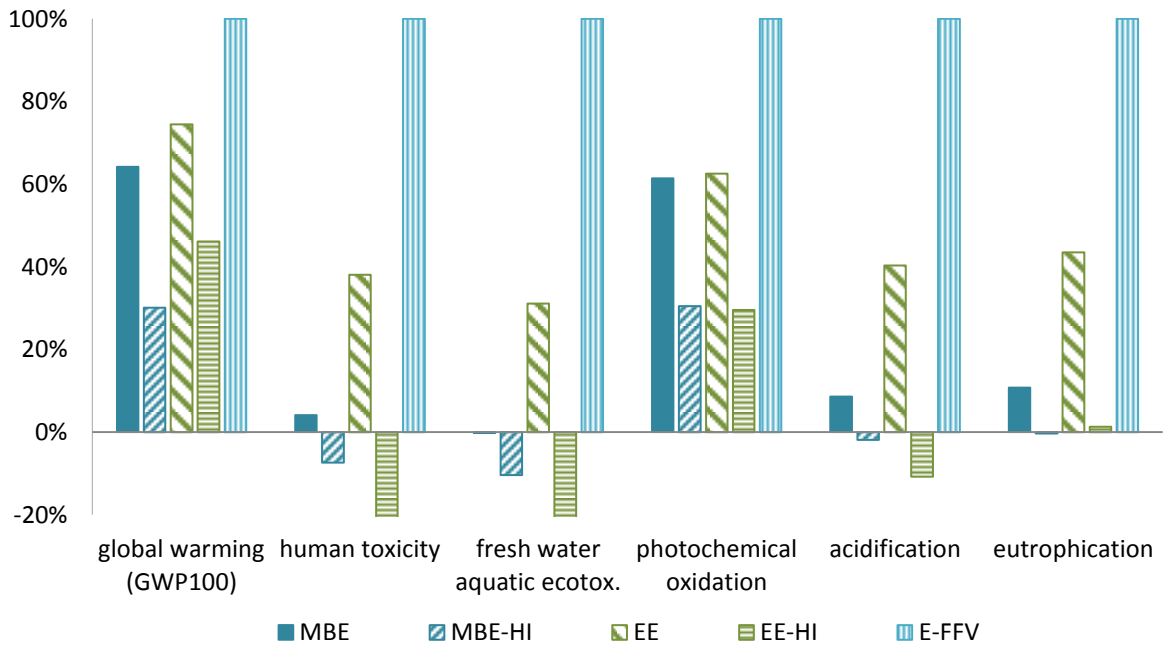


Figure 7-3: Comparison of the environmental performance of the bio-ethanol scenarios for the expanded system functionality of 1.54 x 10^4 kWh electricity and 6.21 x 10^4 km driven for SYSTEM 1

Overall, the power generation scenarios have significantly better environmental performance within all categories. The biogas scenarios performed well within all impact categories, whereas the ethanol-fuel scenario performed poorly for all categories. The heat integration scenarios both perform better than their counter parts without heat integration. The following sub-sections evaluate the individual processes within the expanded systems for the selected impact categories (see Appendix D for tables detailing these results).

7.1.2.1 Global warming (GWP100) potential

One of the major contributors to the greenhouse gas emissions for both the power generation and transport scenarios is the disposal of the process sludge generated during production. All the scenarios produce similar amounts of process sludge. The sludge is sent to landfill where it produces landfill gas, which consists predominantly of the greenhouse gases (GHGs), CH_4 and CO_2.

Another major contributor to this impact category is the emissions associated with the coal-based electricity. Keeping in mind that the overall fossil energy consumption of the ethanol transport scenario is in fact lower than that of the power generation scenarios (Figure 7-2), the poor performance of the former therefore indicates that the GHG emissions associated with coal-based electricity generation exceed those of the gasoline combustion processes. The heat integration counterparts of both the biogas- and ethanol based scenarios performs much due to the need for less coal-based heat.

7.1.2.2 Human toxicity potential

This impact category is measured in 1,4-DB equivalents, which results from the contribution of a large number of chemicals which may potentially contribute to various negative human health effects. The identification of the major contributing substances is

not as simple as that of the GWP, but it is clear that it is dominated by coal-related activities.

The major contributor is the emissions from the tailings of coal mined for electricity and heat generation, and so, as expected, the fossil-based electricity and heat consumption of the scenarios dictate its environmental performance within this particular category. The emissions associated with the gasoline combustion are insignificant in comparison to that of the coal-based electricity and particularly heat.

It is therefore not surprising that the power generation scenarios dominate once again, as less coal-based electricity is required for system expansion due to the generation of the bio-energy electricity. In addition to this, the ethanol fuel production process requires more energy. Similarly, the integration of heat co-generated from bio-energy shows significant improvements to all the power generation options due to the replacement of the traditional coal-based alternative.

7.1.2.3 Fresh water aquatic eco-toxicity potential

As with the human toxicity potential, the major contributor to this category are the emissions from the tailings of coal mined for coal-related activities such as electricity and heat generation. The emissions associated with the generation of electricity and heat, as well as gasoline production, is also quite significant. So, as expected, the ethanol scenarios EE and E-FFV perform poorly due to the high heat requirements for the production phase. The integration of bioenergy-based heat therefore shows significant improvement for the ethanol scenario (EE-HI) and the biogas scenario (MBE-HI).

In comparison to the power generation scenarios, the E-FFV scenario performs poorly in this impact category. This is primarily due to the 1.54×10^4 MJ of coal-based electricity added for system expansion.

7.1.2.4 Photochemical oxidation potential

As with the GWP, the photochemical oxidation potential is also dictated by the process sludge disposal emissions and the heat and electricity emissions, particularly CH_4 and CO; and so the transport scenario (E-FFV) performs poorly. As expected, the bio-energy based electricity scenarios perform better as they replace the fossil-based alternative.

Significant improvement is observed for the heat integration options. The gasoline vehicle emissions contributes significantly to the power generation scenarios; however the emissions related to the generation of electricity far outweigh that of the combustion of gasoline.

7.1.2.5 Acidification potential

The acidification potential (AP) results from the formation of acids from SO_2 and NO_X emissions reacting with water vapour. It is not surprising that the major contributor to the AP is the coal-based electricity consumption due to the high emissions of SO_X, NO_X and particulates associated with South African coal-based electricity generation (von Blottnitz, 2006). Second to the electricity generation, coal-based heat generation also contributes to the SO_2 equivalents. The gasoline contributions are much lower than that associated with both the heat and electricity generation processes.

The transport option E-FFV, therefore, performs poorly in comparison to all the power generation scenarios due to system expansion. The improvements related to heat integration are significant for both the biogas and ethanol options.

7.1.2.6 Eutrophication potential

The eutrophication potential (EP) exhibits similar trends to that of the AP, with the coal-based electricity generation being the largest contributor to this impact category. In addition to this, the subsequent coal tailings also result in significant emissions,

contributing further to the EP. As with the AP, the transport scenario performs poorly as a result of the extensive coal-based electricity use for system expansion purposes.

With respect to the power generation scenarios, the biogas options (MBE and MBE-HI) perform better than the ethanol options because of the extensive heat requirements for the latter. In the case of both the biogas and ethanol options, the integration of the biogas-based heat shows significant improvements within this category.

A summary of the impact assessment results and an interpretation thereof will be presented in Section 7.3. The following section describes the procedure followed to expand SYSTEM 2 and presents the impact assessment results thereafter.

7.2 Comparison of expanded systems for bio-methane scenarios for SYSTEM 2

As with SYSTEM 1, the power generation scenario options (SYSTEM 2) were expanded through the addition of coal-based electricity to generate an electrical output of the same magnitude for all scenarios (Table 6-13). The maximum electrical output of 1.53 x 10^4 kWh was generated through the co-digestion of AW (Figure 7-4). As discussed in Section 3.3.2.4.2, *hypothesis 2* considers the effects of co-digestion on the technical and environmental performance of these options by comparing it to the mono-digestion of 67 tons WPS on the basis of digester volume, which corresponds to 20 tons VS. The co-digestion scenario was thus scaled down to 52 tons WPS and 15 tons of AW, which correlates with the 20 tons VS.

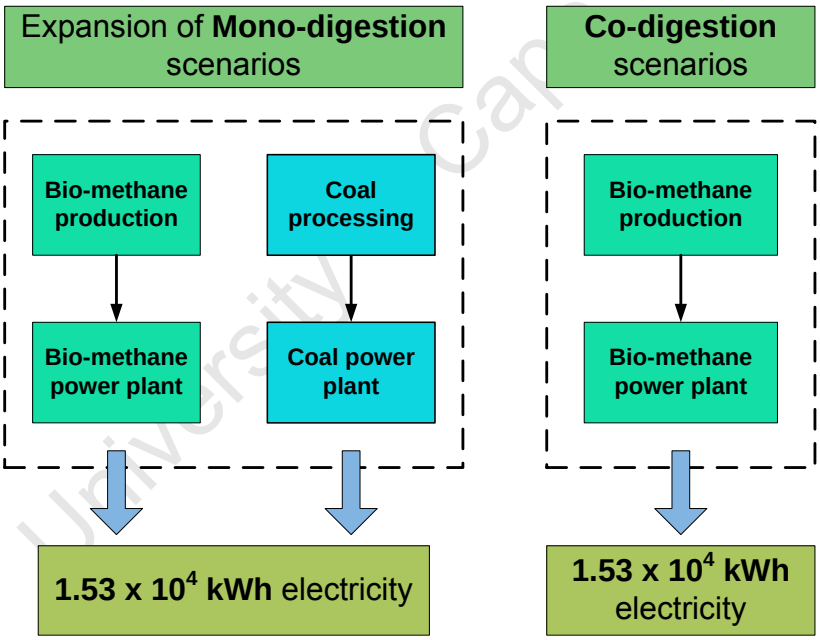


Figure 7-4: Schematic of application of system expansion approach to achieve an overall functional output of 1.53 x 10^4 kWh electricity for SYSTEM 2

The following section presents a summary of the major flows associated with the expansion of the bio-methane system and the results of the impact assessment carried out in SimaPro using the CML 2 baseline 2000 V2.03 method.

7.2.1 Procedure of system expansion for SYSTEM 2

The graph below (Figure 7-5) depicts the overall fossil energy consumption and the contributing energy processes after system expansion. A summary of the major fossil energy flows is presented in Appendix 9.4.

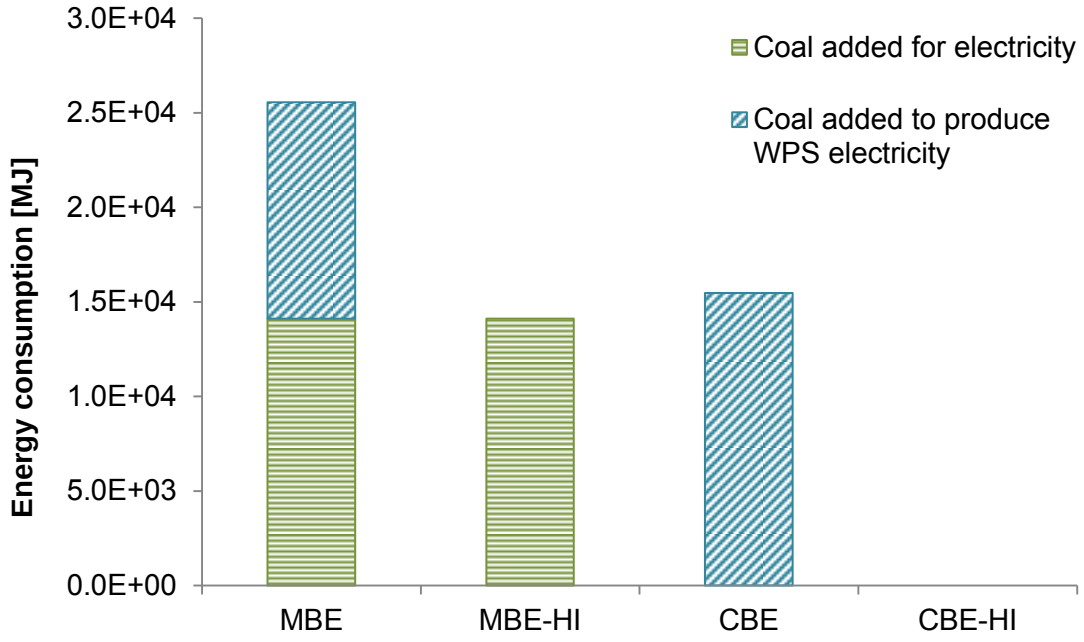


Figure 7-5: Overall consumption of fossil fuels to achieve an overall functional output of 1.53 x 10^4 kWh electricity for SYSTEM 2

Because the co-digestion scenarios (CBE and CBE-HI) generated the highest electricity output, 1.53 x 10^4 kWh, no coal-based electricity was added for system expansion and so these scenarios displayed the lowest fossil energy consumption of 1.55 x 10^4 MJ(CBE) and 0 MJ (CBE-HI).

The integration of heat (MBE-HI and CBE-HI) displayed substantial improvement with respect to the overall fossil energy input. The following section presents the impact assessment results.

7.2.2 Impact assessment results for expanded systems

The following figure illustrates the comparative performance of the scenarios involving the mono-digestion (MBE and MBE-HI) and co-digestion (CBE and CBE-HI) of WPS and AW for the production of biogas for use in a CHP.

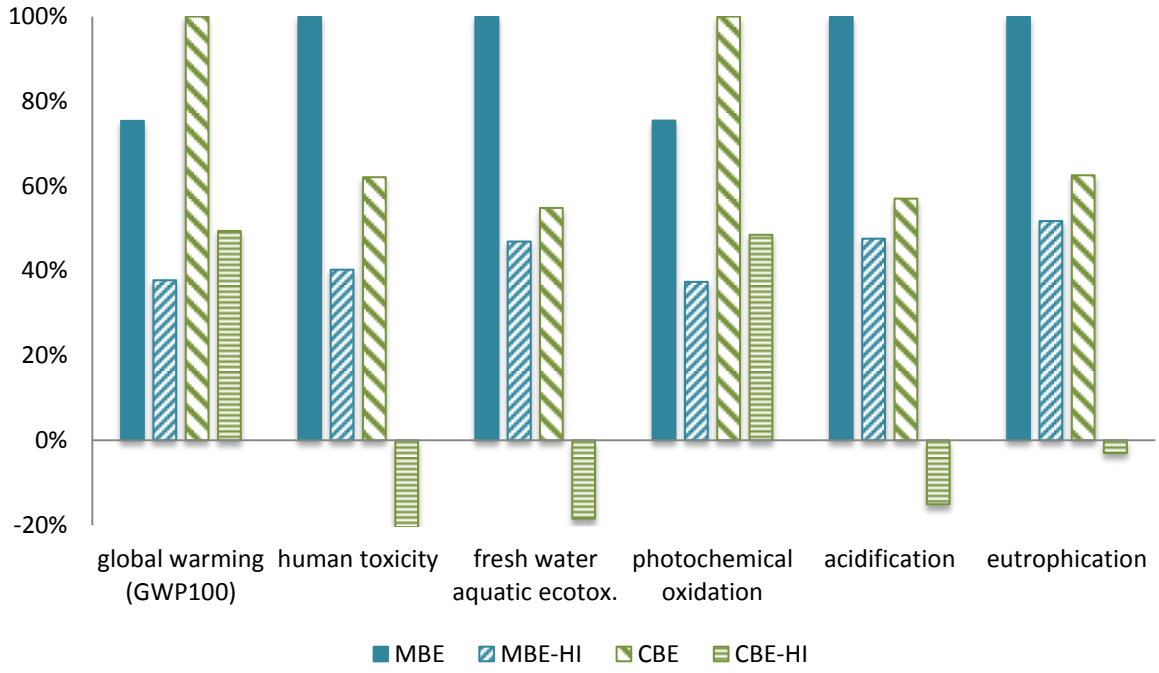


Figure 7-6: Comparison of the environmental performance of the scenarios for the expanded system functionality of 1.53 x 10^4 kWh electricity for SYSTEM 2

From Figure 7-6, the advantage of the co-digestion scenarios over the mono-digestion scenarios is quantified. In addition to this, the integration of the generated heat displays significant improvements to the majority of the impact categories assessed, with the exception of the GWP and POP, for which improvements appear to be marginal. The individual processes within the expanded systems are briefly discussed in the following sub-sections for the selected impact categories, as the impact categories were already discussed extensively in the previous section (see Appendix D for tables detailing these results).

7.2.2.1 Global warming (GWP100) potential

As discussed in Section 7.1.2.1, the main contributor to this impact category is the process sludge generated, on a kg VS basis. The effects of the coal-based electricity are negligible in comparison. The mono-digestion scenarios (MBE and MBE-HI) generate less process sludge than the co-digestion scenarios (CBE and CBE-HI) and therefore results in a GWP. The effect of heat integration results in significant improvements.

7.2.2.2 Human toxicity potential

In Section 7.1.2.2 it was found that the dominating factor in this impact category (*HTP*) was the emissions associated with the disposal of the coal tailings produced through electricity and heat generation from coal. The co-digestion scenarios therefore perform much than the mono-digestion scenarios as no coal-based electricity is required for system expansion.

The integration of the biogas-based heat shows marked reduction within this category due to the avoided emissions associated with the replaced coal-based heat, thus resulting in saved emissions. This is particularly clear with the co-digestion scenario involving heat integration (CBE-HI), where the avoided coal-based heat emissions far exceed those associated with the other processes.

7.2.2.3 Fresh water aquatic eco-toxicity potential

As indicated in Section7.1.2.3, this impact category is dominated by the coal-based electricity and heat in much the same way as the *human toxicity potential* and so behaves in a similar manner.

7.2.2.4 Photochemical oxidation potential

As with the GWP, this impact category is dominated by the process sludge generation and the coal-based electricity (see Section 7.1.2.4 for detailed description). The mono-digestion scenarios (MBE and MBE-HI) outperform the co-digestion scenarios (CBE and CBE-HI) in this category; and heat integration results in only marginal improvements each scenario.

7.2.2.5 Acidification potential

This impact category (*AP*) is dominated by the generation of coal-based electricity and, to a lesser extent, heat (see Section 7.1.2.5 for detailed description). As with the *HTP* the co-digestion scenarios dominate and heat integration results in significant improvements to this category.

7.2.2.6 Eutrophication potential

Section 7.1.2.6 shows that this impact category (*EP*) displays similar trends to that of *AP*; and so the mono-digestion scenarios perform poorly in comparison to the co-digestion scenarios. However, the emissions associated with the generation of biogas-based electricity also contribute quite significantly to this impact category. This is especially evident within the co-digestion scenarios (CBE and CBE-HI) as no electricity was added for system expansion.

The following section provides a summary of the findings of the LCI and LCIA results, along with a discussion.

7.3 Summary and discussion of the LCI and LCIA results

The primary goal of this study was to explore the life cycles of the two bio-energy products, bio-ethanol and bio-methane, from a waste paper sludge feedstock, including their end use of either power generation or transport fuel, and to compare them based on their technical and environmental performance.

The life cycle interpretation phase of an LCA provides a summary of the *life cycle inventory* (LCI) and *life cycle impact assessment* (LCIA). An evaluation of these results was carried out so as to identify significant issues. The following sub sections present the summary of results along with these key findings.

7.3.1 GHG reduction through WtE technology

One of the biggest contributors to the GWP of the bio-energy systems assessed was the landfill emissions of the waste process sludge generated. Bearing in mind that the reference flow of the systems corresponded to approximately 20 tons VS, then the process sludge produced was reduced substantially, with reduction up to 83% for the biogas scenarios involving mono-digestion (MBE and MBE-HI). In comparison to a "business-as-usual" scenario involving the disposal of the WPS and AW in a landfill site, these reductions then translate into significant GHG savings from landfill diversion.

Another major contributor to the GHG emissions is that associated with the coal-based electricity and heat used for the production process. In comparison to a business-as-usual scenario for energy production one could consider the amount of GHG emission savings due to the replacement of coal for electricity generation. The following tables (Table 7.1 and Table 7.2) illustrate these GHG savings in relation to each other for each scenario.

Table 7-1: Relative reductions of GHG emissions (CO_2 equivalents) from landfill diversion

	MBE	MBE-HI	CBE	CBE-HI	EE	EE-HI	E-FFV
GHG reductions from landfill diversion	6.7E+04	6.7E+04	5.38E+04	5.38E+04	6.6E+04	6.6E+04	6.6E+04
	83%	83%	**74%**	**74%**	82%	**82%**	82%

The CO_2 equivalent of the landfill emissions for the business as usual scenario was calculated for the waste feed streams of 20 kg VS, based on the correlations used in the CML 2 baseline 2000 V2.03 method. The emissions generated from the process waste sludge of the various scenarios was then calculated in the same manner and subsequently deducted from the business-as-usual scenario emissions to determine the "saved GHG emissions". Based on the results in Table 7.1, it is evident that all waste-to-energy scenarios result in considerable reduction in the GHG emissions associated with the business as usual scenario. Reductions of up to 83% and 82% can be achieved when biogas and ethanol electricity is generated.

Similarly, for the electricity scenarios the GHG emissions associated with the business-as-usual scenario was calculated. Essentially, the amount of coal to generate the same amount of electricity as the bio-energy options was calculated based on Eskom (2006), which states that 1.8 kg CO_2 is emitted for every kg of coal used for electricity generation. The emissions for the coal-based electricity and/or heat used in the bio-energy production phase was then calculated and deducted from the business as usual scenario to determine the GHG emission savings (Table 7-2).

Table 7-2: Relative reductions of GHG emissions (CO_2 equivalents) from coal replacement

	MBE	MBE-HI	CBE	CBE-HI	EE	EE-HI
GHG reductions from replaced coal	8.5E+03	9.6E+03	1.15E+04	1.30E+04	3.7E+04	4.6E+04
	88%	**100%**	88%	**100%**	**79%**	99%

As expected, all scenarios with heat integration (MBE-HI, CBE-HI and EE-HI) resulted in 100% GHG reductions associated with coal-use, as both biogas-based electricity and heat were integrated into the bio-energy production phase. The biogas scenarios without heat integration also performed well, whereas the ethanol option without heat integration performed poorly. This is on account of the high thermal requirements associated with the distillation unit. In comparison to the GHG reductions associated with the diversion of waste from landfill, those from the coal replacement are much less.

7.3.2 Heat integration for improved energy performance

In the electricity scenarios, the bio-energies produced were studied for the co-generation of electricity and useful heat. Some of this heat could be used for the thermal requirements of the bio-energy production. In all cases, this heat integration resulted in coal savings and thus improved energy performance. The options involving heat integration showed a marked improvement to its counterpart for all environmental impact categories.

7.3.3 The potential of bio-energy in a coal-intensive climate

To assess the potential of bio-energy from WPS and the application thereof five scenarios were developed for comparison (SYSTEM 1). These consisted of two biogas-based electricity generation scenarios (MBE and MBE-HI), two bio-ethanol derived electricity generation scenarios (EE and EE-HI) and an ethanol-based vehicle scenario (E-FFV). A net energy gain was achieved for all scenarios, with respect to the production

phase. The major flows associated with these scenarios including the end-use applications were presented in Table 6-12 in Section 6.2.3.

To properly compare the bio-energy scenarios the systems were expanded through the addition of the conventional fossil-based alternatives (Figure 7-1) to generate a combined functional output of 6.21 x 10^4 km driven and 1.54 x 10^4 kWh (5.45 x 10^5 MJ) of electricity (Figure 7-1). The ethanol-based electricity option (EE) displayed the largest fossil energy consumption after system expansion (Figure 7-2); whereas the EtOH-fuelled flex-fuel vehicle option (E-FFV) required the least fossil-based energy. The biogas-scenarios (MBE and MBE-HI) required only slightly more fossil based energy.

These expanded systems were modelled in SimaPro and assessed using the CML 2 baseline 2000 V2.03 method. The following table highlights the scenarios with the highest (red) and (green) lowest emissions within the various impact categories.

Table 7-3: Summary of environmental performance of expanded SYSTEM 1

	Warming (GWP100)	Human toxicity	Fresh water aqua. tox.	Photochem. oxidation	Acidification potential	Eutroph. potential
	kg CO_2 eq	kg 1,4-DB eq	kg 1,4-DB eq	kg C_2H_4 eq	kg SO_2 eq	kg PO_4 eq
MBE	4.45E+04	6.91E+02	-9.38E+00	1.16E+01	2.68E+01	1.64E+00
MBE-HI	**2.09E+04**	-1.24E+03	-4.19E+02	5.75E+00	**-5.73E+00**	**-4.97E-02**
EE	5.16E+04	6.40E+03	1.25E+03	1.18E+01	1.25E+02	6.61E+00
EE-HI	3.20E+04	**-3.54E+03**	**-8.70E+02**	**5.58E+00**	-3.36E+01	2.01E-01
E-FFV	**6.93E+04**	**1.68E+04**	**4.02E+03**	**1.89E+01**	**3.11E+02**	**1.52E+01**

Overall, the power generation scenarios dominated, particularly the biogas and ethanol based scenarios involving heat integration (MBE-HI and EE-HI). With respect to the ethanol scenarios, the results agree with that of Melamu and Von Blottnitz (2009), who

found that bio-ethanol for electricity generation performed significantly better than bio-ethanol as a transport fuel with respect to the environmental performance. For both the global warming potential and photochemical oxidation the biggest contributor was the process sludge, which was discussed in detail in Sections 7.1.2.1 and 7.1.2.4. The remaining impact categories were dominated by the coal-based electricity and heat processes, particularly that added for system expansion. The electricity required for the bio-energy production phases was negligible in comparison.

Based on these results, it is quite clear that the environmental impact assessment is highly dependent on the efficiency of destruction of components of the waste which would lead to emissions from landfill, and thereafter to the source of the electricity and heat. The 2nd factor cautions that the results of this study are influenced by and therefore also limited to the coal-intensive economy of South Africa. The subsequent conclusions and recommendations would be restricted to this particular scope.

7.3.4 Co-digestion for improved performance of power generation scenarios

The effects of co-digestion of carbon-rich paper waste with nitrogen rich substrates on the bio-methane yield were assessed in the experimental analysis with promising results, detailed in Chapters 4 and 5. To build onto this assessment, SYSTEM 2 was developed to test the effects of co-digestion on the end-use performance. In addition to the two bio-methane scenarios considered in SYSTEM 1, two scenarios involving the production of bio-methane through the co-digestion of WPS and AW for the cogeneration of power and heat were developed for SYSTEM 2. The major flows obtained for the production phase and end-use application of these scenarios were depicted in Table 6-11 and Table 6-13 in section 6.2.2, respectively.

The co-digestion scenarios (CBE and CBE-HI) generated the highest electricity output and so, as with SYSTEM 1, the scenarios were expanded to generate a combined output of 1.98 x 10^4 kWh electricity with the addition of coal-based electricity (Figure 7-4). These

expanded systems were modelled in SimaPro and assessed using the CML 2 baseline 2000 V2.03 method, generating the following impact assessment results (Table 7-4).

Table 7-4: Summary of environmental performance of expanded SYSTEM 2

	Warming (GWP100)	Human toxicity	Fresh water aqua. tox.	Photochem. oxidation	Acidification potential	Eutroph. potential
	kg CO_2 eq	kg 1,4-DB eq	kg 1,4-DB eq	kg C_2H_4 eq	kg SO_2 eq	kg PO_4 eq
MBE	**4.74E+04**	**3.23E+03**	**7.71E+02**	**1.16E+01**	**6.20E+01**	**3.49E+00**
MBE-HI	**2.37E+04**	1.30E+03	3.61E+02	**5.73E+00**	2.95E+01	1.81E+00
CBE	6.28E+04	2.00E+03	4.23E+02	1.53E+01	3.54E+01	2.18E+00
CBE-HI	3.10E+04	**-6.62E+02**	**-1.43E+02**	7.43E+00	**-9.40E+00**	**-1.06E-01**

The co-digestion scenarios outperform the mono-digestion scenarios for most impact categories, and only marginally so for the GWP and POP. As previously discussed, the biggest contributor to these two impact categories was the efficiency of the components of the waste which would lead to landfill emissions. That is, the quantity of process sludge that is generated. However, it should be noted that both the mono-digestion and co-digestion scenarios result in substantial VS reductions of the initial feed and, as discussed in Section 7.3.1, in comparison to the "business-as-usual" scenario of subsequent landfilling of the waste feedstock, all scenarios present a better alternative. The remaining categories were dominated by the coal-based electricity and heat generation processes, resulting in increased emissions for the mono-digestion scenarios due to the system expansion.

The final chapter concludes this dissertation by reiterating the objectives and summarising the major findings. It will then revisit the hypotheses put forward, followed by recommendations.

8 CONCLUSIONS AND RECOMMENDATIONS

8.1 Objectives of the research

The pressing need for alternative methods of waste management strategies in cities in developing countries, such as the City of Cape Town, has led to increased interest in energy recovery from waste. However, owing to the high proportion of wet organic waste, it will be necessary to take material-specific approaches going beyond bulk incineration. Life Cycle Assessments (LCAs) have shown that there is a large potential in bio-energy production from waste papers and cellulosic waste sludge. Cellulosic ethanol production and anaerobic digestion for bio-methane production are therefore considered as an alternative to the traditionally used thermal technologies.

The primary objective of this study was to evaluate the technical and environmental feasibility of converting waste paper sludge to bio-ethanol and bio-methane for application as a vehicle fuel or for the generation of electricity. A Life Cycle Assessment (LCA) approach was chosen to evaluate and compare the bio-energy systems. A summary of the methods and findings is presented in the following sub-section.

8.2 Major findings

Cellulosic paper sludge displayed promising results for bio-ethanol production, however studies involving its conversion to biogas have been lacking. On the other hand, other sources of waste paper have been described in the literature as an attractive carbon-source for biogas production. An experimental BMP analysis was therefore designed to assess the potential of paper sludge (PS) as a carbon source for biogas production. The following trends were observed.

I. The paper sludge derived from virgin feedstock (PM2 and PM2n in this case) performed better than the recycled paper sludge (PM4o and PM4n) for both mono-digestion and co-digestion per g VS_{FED}.

II. The results show that co-digestion of PS with N-rich substrates AW and FW can boost the expected bio-methane yields; however the performance with regards to the % improvement (per g VS) varied across the different seed inocula tested, resulting in no improvement in some cases.

III. The bio-methane yield of a particular co-digestion scenario (per g VS basis) was consistent across all seed inocula. It can be concluded then that co-digestion may not always result in improvements with respect to the expected yields, but should aid in the stability of a particular system.

To compare the bio-energy systems, four power generation scenario options and one transport scenario option were developed (SYSTEM 1). Based on the experimental BMP analysis a second system (SYSTEM 2) was developed to assess the effects that co-digestion may have on the end-use applications. These scenarios were modelled and assessed in SimaPro using the CML 2 Baseline 2000 V2.03 method. The following conclusions were drawn from the assessment.

IV. ***GHG reduction through WtE technology***. The GWP of the bio-energy systems assessed were highly dependent on the efficiency of destruction of volatile components of the waste and thereafter to the source of the electricity and heat. A "business-as-usual" scenario involving the disposal of the WPS in a landfill site for approximately 20 tons of VS for both SYSTEM 1 and 2, generating substantial GHG emissions. The implementation of all the bio-energy options result in VS reductions, up to 83% in the case of the bio-methane scenarios. These reductions translate into significant GHG savings, as do those associated with the replacement of coal for electricity generation, up to 100% for both the biogas-based scenarios (MBE-HI and CBE-HI) and the ethanol-based electricity scenario (EE-HI).

V. ***Heat integration for improved energy performance***. Heat is co-generated along with that of electricity using biogas in a CHP; in the case of the ethanol scenario additional biogas could be produced from the waste process sludge for this purpose. In all cases, the use of this heat for the thermal requirements of the

bio-energy production phase resulted in significant coal savings and thus improved energy and environmental performance. The biogas options involving HI demonstrated coal savings of 0.6 tons (MBE-HI) and 0.8 tons (CBE-HI). The ethanol options resulted in a coal saving of 0.5 tons (EE-HI) through the integration of the biogas-based heat generated from the process waste sludge.

VI. ***Potential of bio-energy in a coal intensive economy***. A system expansion approach was used to compare the performance of the power generation and transport scenarios. This procedure involved the addition of fossil energy carriers, gasoline and coal-based electricity, to generate the combined functional output. The power generation scenarios dominated in all environmental impact categories, particularly the scenarios involving HI (MBE-HI and EE-HI). In comparison to the other electricity scenarios the ethanol electricity option without heat integration performs poorly for all criteria. This is on account of the high heating requirements of the ethanol production process; more than double that of the biogas alternatives per MJ electricity generated. The biogas option without HI (MBE) requires only ~0.3 MJ primary fossil energy for every MJ of electricity generated (MJ/ MJ); and the option with heat integration requires no fossil energy input (MBE-HI). The ethanol option with heat integration (EE-HI) requires only ~0.1 MJ primary energy for every MJ of electricity generated.

VII. ***Co-digestion for improved performance of biogas-based electricity***. As expected, due to the increased yields of the co-digestion scenarios (CBE and CBE-HI) and thus increased electricity output per unit digester volume, they outperformed the mono-digestion scenarios (MBE and MBE-HI) in that regard and most environmental metrics. Due to the lower volatiles reduction of the co-digestion scenario, a marginal improvement was displayed for the GWP and POP impact categories after system expansion.

8.1 Validation of hypotheses

The aim of the dissertation was to substantiate the following hypotheses:

Hypothesis 1: Relatively uncontaminated forms of non-recyclable paper will become an attractive feedstock for commercial fuel bio-ethanol production, especially where flex-fuel vehicles are wide-spread – however, this will not represent the most energy-efficient or environmentally friendly energetic usage of this type of waste paper.

Ethanol-fuel production from paper sludge as a replacement for conventional fuel results in a net energy gain, which is in line with the findings of recent Life Cycle Assessments on WtE systems (Von Blottnitz and Curran, 2007). In comparison to other cellulosic waste sources, paper sludge feedstock does not require much or even any pre-treatment due to its short cellulose fibres, a resultant of extensive processing. Therefore, savings on fossil-energy for pre-treatment and enzyme costs (Lark *et al*, 1997) as well as the abundant supply thereof makes paper sludge a very attractive option for fuel-ethanol production.

However, within a South African context which displays a very coal-intensive economy, a scenario involving ethanol production for the use in a flex-fuel vehicle is not the option with the highest environmental benefits, as shown by the comparison to the ethanol- and biogas-based electricity alternatives assessed, as discussed in the *Key Finding VI*.

The second hypothesis stated that

> ***Hypothesis 2:*** Forms of non-recyclable and non-recoverable paper which are more contaminated will co-digest well in anaerobic digesters set up to recover energy from waste and reduce volumes for disposal, boosting gas yields per unit of digester volume, especially when used to adjust carbon to nitrogen ratios.

Contamination was not itself investigated here, but a co-digestion with a protein-containing substrate was used as a proxy for the presence of other potentially trouble-some substances. Based on the bio-chemical methane potential (BMP) assays involving the co-digestion of PS with N-rich substrates (AW and FW), it can be concluded that increased bio-methane yields per g VS_{FED} can be achieved through co-digestion. However, the extent of improvements is dependent on the seed inoculum and particular material used. All the materials digested displayed substantial reductions in solid waste volumes.

8.2 Recommendations for further research

Based on the results of the experimental work involving BMP assays of waste paper sludge, the following recommended research is proposed:

- The BMP analyses were carried out at a constant temperature of 37° C and in a batch mode configuration. These ideal conditions are not always realistic at a large-scale. In addition to this, the sensitivity of the BMP assays at such a small scale hindered the analysis of the system beyond that of the biogas production and methane composition. It is therefore recommended that the a selection of the assay mixtures be scaled-up to 2 L batch-fed reactors so as to allow for more analyses such as the change of pH, VFAs, COD and VS to better understand the biogas systems.

- The waste paper sludge derived from recycled paper, whilst yielding less biogas, performed much faster than that derived from virgin paper. As hydrolysis is considered to be the main rate-limiting step in AD, this was expected as the cellulose strands of the latter are much shorter than the former due to extensive recycling. The pre-treatment of the PM2 should therefore improve the rate of biogas production. BMP assay including pre-treatment methods are recommended to evaluate its effect on production rate.

Based on the LCA results the following recommendations are proposed:

- From an environmental perspective, the findings of this dissertation support those of earlier work referred to in the literature review that a focus on liquid bio-fuels is too narrow. In a coal-intensive economy, significant environmental improvements are possible by replacing coal-based energy products.

- A particular additional recommendation from this current work is that biogas technology should be considered much more seriously in "bio-energy" discussions.

- Finally, it is recommended that the research be extended to include the social and economic implications of the bio-energy from waste paper systems, so as to also cover the other two spheres of a fuller sustainability analysis. This should include a comparison to the "business-as-usual" scenarios of the traditional fossil-energy based electricity and gasoline.

9 APPENDICES

9.1 Appendix A: Preliminary energy yield calculations from waste paper

Literature values for RPS compositions

Lark et al (1996)	RPS-1	RPS-2
Moisture	62	64
	% (dry basis)	
Total carbohydrates	59	55.5
Glucose	50.7	48
Xylose	8.3	7.4
Other	41	44.5

	Marques (2007)	Kadar (2004)
Cellulose	34.1	45
Xylan	7.9	
Lignin	20.4	
Ash	29.3	
Protein	4.8	
Fats	3.5	

Basis used for energy yield calculations

LHV of cellulose (dry)*	16.0	[MJ/kg]
Basis for calculations, RPS (VS)	1	[kg]

RPS conversion to bio-ethanol

	(Lark *et al*, 1996)	(Kadar *et al*, 2004)	
Moisture content	63%	-	
Total solids content	37%	-	
Total carbohydrates (VS of TS)	59%		
Cellulose composition (dry basis) *	-	45%	
EtOH concentration	35	-	[g/L]
Substrate concentration (dry RPS)	190	-	[g/L]
Yield	0.184	-	[kg EtOH/kg dry RPS]
	-	0.3295	[kg EtOH/ kg cellulose]
LHV (EtOH)	26.7	26.7	[MJ/kg EtOH]
Energy yield	**8.34**	**8.80**	**[MJ/kg VS]**
Portion of rps LHV recovered into ethanol	52%	55%	

Volatile and total solids calculations for the RPS

	Mass (g)		
Empty Crucible	21.80	22.14	22.02
Crucible + Waste	23.64	24.22	24.96
Crucible + waste after Oven @ 80C	21.92	22.31	22.19
Crucible+ waste after Oven @ 550C	21.88	22.26	22.14
Total solids fraction	0.06	0.08	0.06
Volatile Solids fraction	0.33	0.30	0.31
Average Total solids (TS) %	6.88		
Water content (%)	93.12		
Average Volatile solids (% of TS)	31.45		
Average VS (of total waste) %	2.16		

RPS conversion to bio-methane (Compiled using data from Munganga, G., 2010)

Total solids (TS)	6.88%	
Volatile solids of TS	31.45%	
Yield	138.5	[ml CH_4/ g VS]
	0.1385	[m^3 CH4/ kg VS]
LHV (CH_4)	34.6	[MJ/ m^3]
Energy yield	**4.79**	**[MJ/kg VS]**
Portion of rps LHV recovered into biogas	30.0%	

Bio-methane production at mesophilic temperatures (35°C) (Gunaseelan, 1997)

	% TS	% moisture	% VS of TS	CH4 yield (m^3/ kg VS)	CH_4 (m3)	Energy (MJ/kg dry sample)	Energy (MJ/kg VS)
Paper samples							
Office	96.2	3.8	92.7	0.369	0.342	11.8	11.4
Corrugated board	94.8	5.2	97.7	0.278	0.272	9.4	8.9
Printed newspaper	91.4	8.6	97.6	0.1	0.098	3.4	3.1
Unprinted newspaper	92.2	7.8	97.9	0.084	0.082	2.8	2.6
Magazines	97.1	2.9	78.1	0.203	0.159	5.5	5.3
Food packing samples							
Uncoated food board	95.8	4.2	98.6	0.343	0.338	11.7	11.2
Coated food board	96.2	3.8	93.3	0.334	0.312	10.8	10.4
Milk carton	96.1	3.9	99.4	0.318	0.316	10.9	10.5
Wax paper	94.6	5.4	98.4	0.341	0.336	11.6	11.0
Levy-1 sample	62	38	92.5	0.205	0.190	6.56	4.1

Mixed Waste Paper conversion to bio-ethanol (Liu *et al*, 2008)

Basis for calculations, MWP (VS)	1	[kg]
Substrate concentration	10	% (w/v)
	100	g/L
EtOH concentration	28.7	g/L
Yield	0.287	[kg EtOH/ kg dry substrate]
EtOH	0.39	[kg]
LHV (EtOH)	26.7	[MJ/kg]
Energy yield	**10.45**	**[MJ/kg VS]**
Portion of MWP LHV into ethanol	**65%**	

Mixed Waste Paper conversion to bio-methane (Gunaseelan, 1997)

Basis for calculations, MWP (VS)	1	[kg]
Total solids	62%	
Volatile solids of TS	93%	
Yield *	0.205	[m^3 CH_4/ kg VS]
LHV (CH_4)	34.6	[MJ/ m^3]
Energy yield	**7.09**	**[MJ/ kg VS]**
Portion of mwp LHV into biogas	**44%**	

*Table 1 (Gunaseelan) - Levy country sample

Corrugated Cardboard conversion to bio-ethanol (Kadar *et al*, 2004)

Basis for calculations, OCC	1	[kg]
Cellulose composition of raw material*	75%	
Yield	0.312	[kg EtOH/ kg cellulose]
LHV (EtOH)	26.7	[MJ/kg]
Energy yield	**8.33**	**[MJ/kg VS]**
Portion of occ LHV recovered as ethanol	**52.1%**	

*Calculated using Hagglund's method (1951)

Corrugated Cardboard conversion to bio-methane (Gunaseelan, 1997)

Basis for calculations, OCC	1	[kg]
Total solids (TS)	94.8%	
Volatile solids of TS	97.7%	
Yield	0.278	[m^3 CH_4/ kg VS]
LHV (CH_4)	34.6	[MJ/ m^3]
Energy yield	**9.62**	**[MJ/ kg dry OCC]**
Portion of occ LHV recovered as methane	**60%**	

Summary of energy yield calculations for various paper-derived feedstock (MJ/kg VS)

	Bio-ethanol Production	Biogas production
RPS	8.34 - 8.80	4.79
MWP	10.45	7.09
OCC	8.33	9.62

9.2 Appendix B: Energy yield calculations of PM2 and PM4

RPS conversion to bio-methane (Compiled using results from Run 1 - SAB)

	PM2	PM4o	PM4n	
Total solids (TS)	32.13%	47.81%	39.98%	
Volatile solids of TS	96.57%	31.12%	40.71%	
Biogas yield	441.24	386.08	271.65	[ml biogas/ g VS]
% CH4	52.00%	49.58%	50.46%	
CH4 yield	229.44	191.40	137.06	[ml CH_4/ g VS]
	0.23	0.19	0.14	[m^3 CH4/ kg VS]
LHV (CH_4)	34.6	34.6	34.6	[MJ/ m^3]
Energy yield	**7.94**	**6.62**	**4.74**	**[MJ/kg RPSdm]**
Portion of rps LHV recovered into biogas	49.6%	41.4%	29.6%	

RPS conversion to bio-methane (Compiled using results from Run 2 - Marquard)

	PM2n	PM4o	PM4n	
Total solids (TS)	32.88%	47.81%	39.98%	
Volatile solids of TS	66.99%	31.12%	40.71%	
Biogas yield	638.66	427.84	274.74	[ml biogas/ g VS]
% CH4	59.88%	53.98%	56.64%	
CH4 yield	382.5	230.96	155.62	[ml CH_4/ g VS]
	0.38	0.23	0.16	[m^3 CH4/ kg VS]
LHV (CH_4)	34.6	34.6	34.6	[MJ/ m^3]
Energy yield	**13.23**	**7.99**	**5.38**	**[MJ/kg RPSdm]**
Portion of rps LHV recovered into biogas	82.7%	49.9%	33.7%	

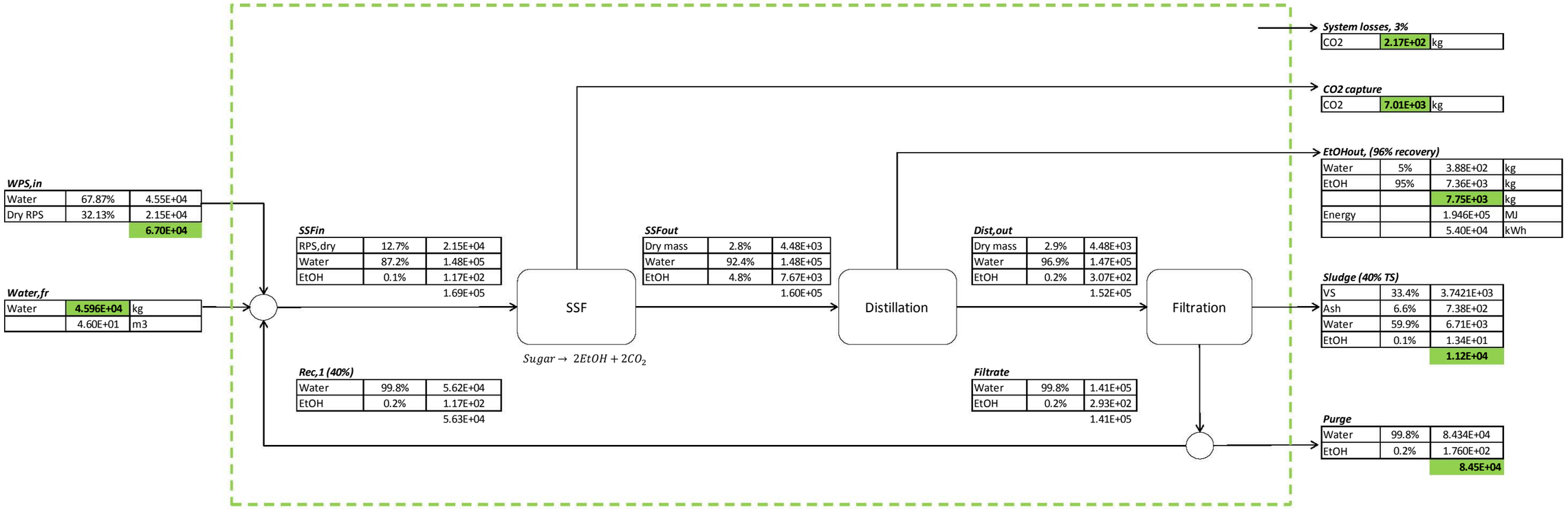
RPS (PM2n) conversion to bio-methane (Compiled using results from Run 3 – SAB repeats)

Total solids (TS)	32.88%	
Volatile solids of TS	66.99%	
Biogas yield	695.88	[ml biogas/ g VS]
% CH4	48%	
CH4 yield	333.5	[ml CH_4/ g VS]
	0.33	[m^3 CH4/ kg VS]
LHV (CH_4)	34.6	[MJ/ m^3]
Energy yield	**11.54**	**[MJ/kg RPSdm]**
Portion of rps LHV recovered into biogas	72.1%	

9.3 Appendix C: Mass and energy balances

ETHANOL OPTIONS

Process flow diagram for 95% ethanol production from WPS for power generation



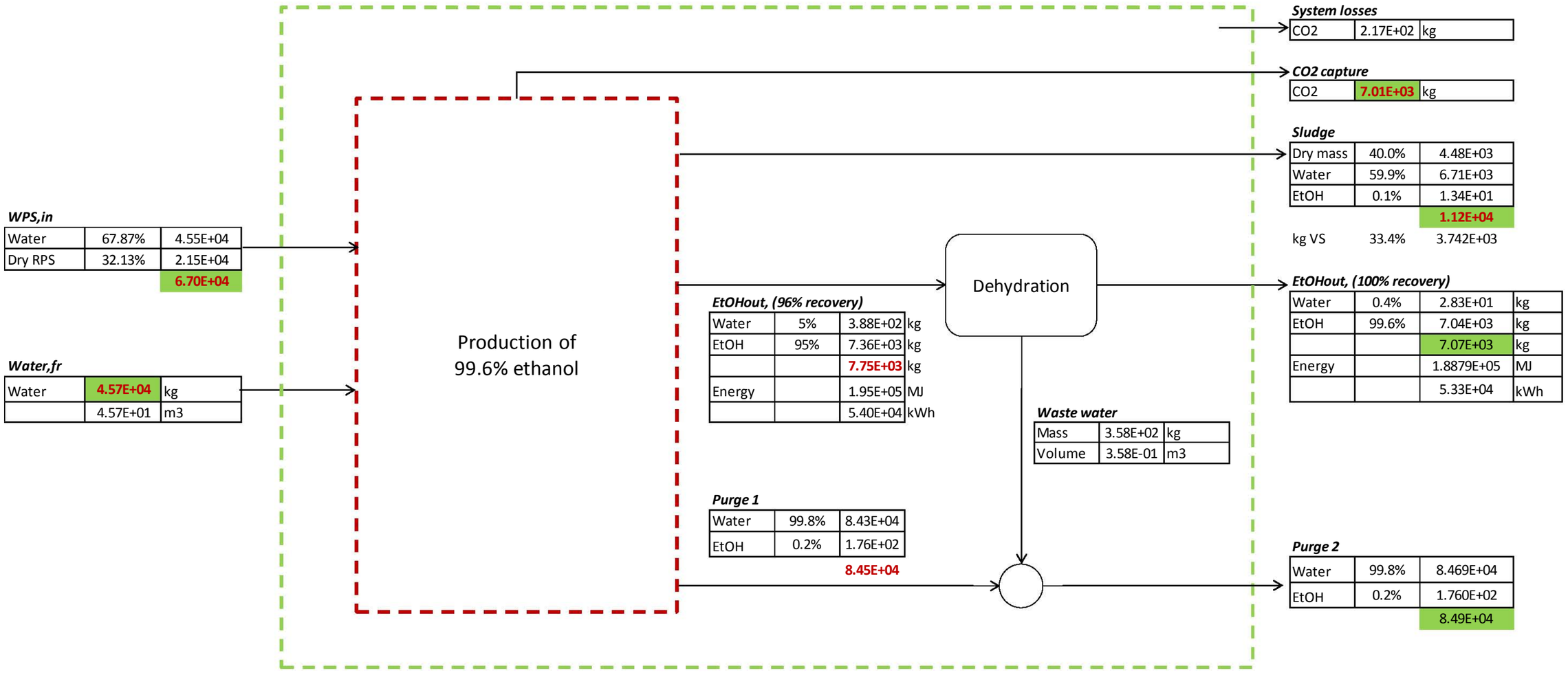
(Lark et al, 1996)	RPS-1	RPS-2
Moisture	62	64
	% (dry basis)	
Total carbohydrates	59	55.5
Glucose	50.7	48
Xylose	8.3	7.4
Other	41	44.5

Lark et al, 1996

Substrate conc (dry RPS)	190	[kg/m3]
EtOH conc.	35	[kg/m3]
Yield	0.184	[kg EtOH/kg dry RPS]
	0.363	[kg EtOH/kg VS*]

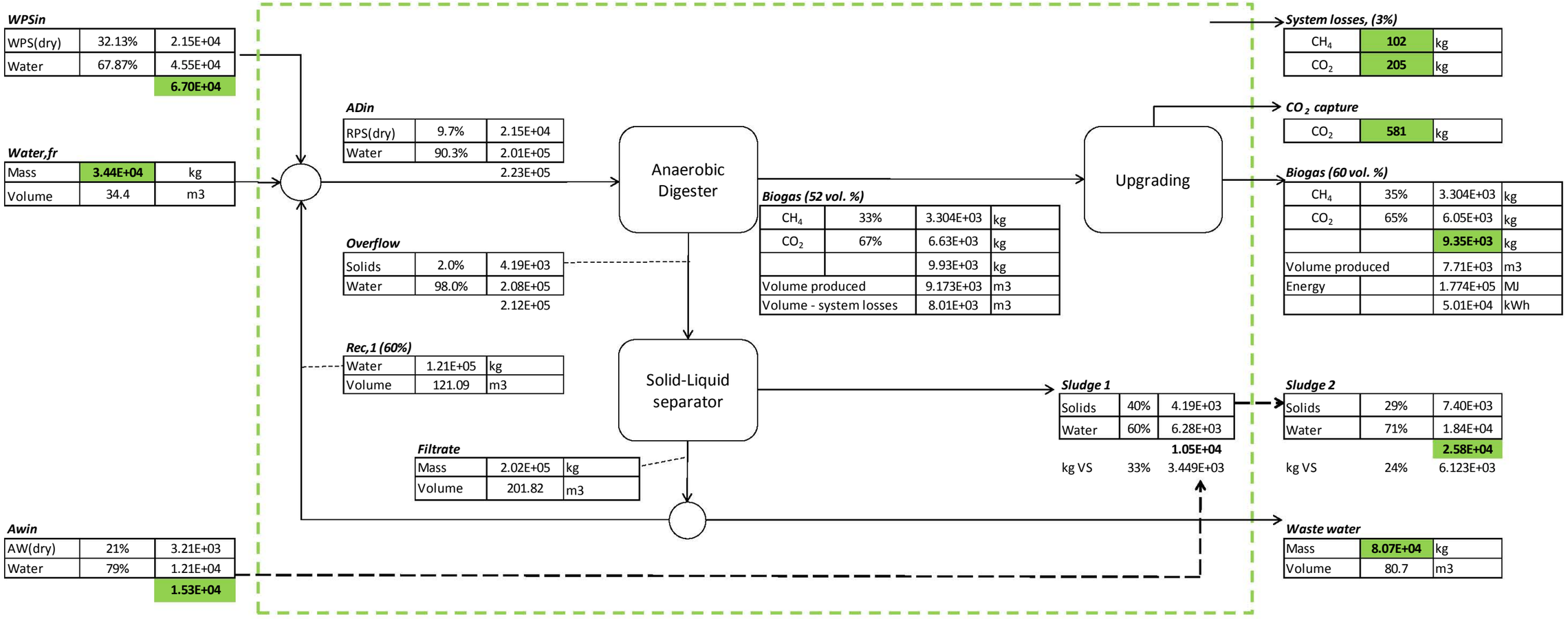
*Assuming, as before, that VS is equivalent to cellulose

Production of fuel ethanol (99.6%) from WPS



BIO-METHANE OPTIONS

Process flow diagram of biogas production from mono-digestion of WPS for CHP



PM2

Water content	67.87%
Total solids (TS)	32.13%
Volatile solids of TS	96.6%

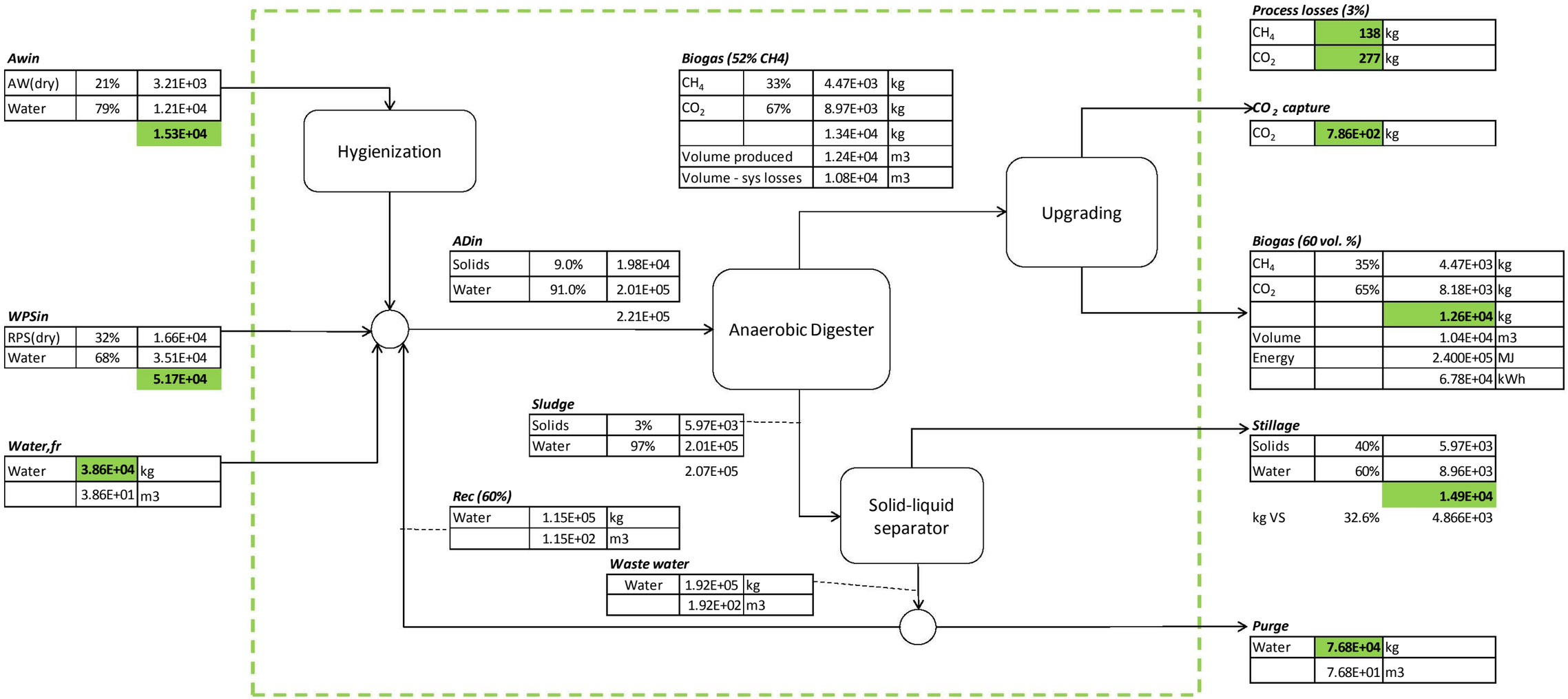
AW

Water content	79.00%
Total solids (TS)	21.00%
Volatile solids of TS	83.23%

Experimental Run 1

Biogas yield	0.441	[m3 biogas/ kg VS]
	0.426	[m3 biogas/ kg RPSdm]
Methane content	52%	

Process flow diagram of biogas production from co-digestion of WPS for CHP



9.4 Appendix D: System expansion

SYSTEM 1: Summary of major energy flow for system expansion

		MBE	MBE-HI	EE	EE-HI	E-FFV
Electricity from WPS	***kWh***	1.13E+04	1.13E+04	1.54E+04	**1.54E+04**	0
Coal added for production for power generation scenarios	***kWh***	0	0	0	0	0
	MJ	1.14E+04	0	1.01E+05	3.527E+03	0
Transport from WPS	***km***	0	0	0	0	**6.21E+04**
Coal added for production for transport scenarios	***MJ***	0	0	0	0	1.01E+05
	kWh	0	0	0	0	5.06E+03
Coal-based energy added for system expansion	***kWh***	4.10E+03	4.10E+03	0	0	1.54E+04
Inherent energy of coal	***MJ***	1.45E+04	1.45E+04	0	0	5.45E+04
Coal added	***kg***	1.94E+03	1.94E+03	0	0	7.30E+03
Gasoline-based mileage added for system expansion	***km***	6.21E+04	6.21E+04	6.21E+04	6.21E+04	0
Inherent energy of gasoline	***MJ***	1.97E+05	1.97E+05	1.97E+05	1.97E+05	0
Gasoline added	***kg***	4.54E+03	4.54E+03	4.54E+03	4.54E+03	0

SYSTEM 1: Impact category results

Major process contributions for the Global Warming (GWP) potential (expressed in kg CO_2 equivalents) for SYSTEM 1

	MBE	MBE-HI	EE	EE-HI	E-FFV
Bio-energy production	4.24E+03	1.32E+03	1.73E+02	1.64E+02	2.17E+02
Electricity from bio-energy	2.76E+03	8.52E+02	1.32E+04	5.23E+03	-
Heat from bio-energy	-	6.37E+00	-	7.07E+03	-
Ethanol, passenger vehicle (PC)	-	-	-	-	1.43E+04
Electricity from coal ZA	-3.79E+03	-3.79E+03	-1.19E+03	-1.44E+03	2.46E+04
Heat from coal ZA	2.45E+03	-7.62E+02	1.04E+04	-6.06E+03	1.31E+04
Gasoline ZA	2.03E+03	2.03E+03	2.03E+03	2.03E+03	-
Gasoline, passenger car (PC)	1.46E+04	1.46E+04	1.46E+04	1.46E+04	-
Wood waste in forest	-2.37E-01	-3.42E+00	9.58E+00	-6.93E+00	3.13E+01
Wood in forest	2.67E+00	3.86E+01	-1.08E+02	7.81E+01	-3.53E+02
Coal from underground mine ZA	-1.55E+01	-2.24E+02	6.28E+02	-4.54E+02	2.05E+03
Process sludge, kg VS basis	2.22E+04	6.91E+03	1.16E+04	1.10E+04	1.45E+04
Total of all processes	4.45E+04	2.10E+04	5.13E+04	3.22E+04	6.85E+04

Major process contributions for Human Toxicity potential (expressed in kg 1,4-DB equivalents) for SYSTEM 1

	MBE	MBE-HI	EE	EE-HI	E-FFV
Electricity from bio-energy	6.39E+00	1.97E+00	1.68E+01	6.64E+00	-
Heat from bio-energy	-	1.47E-02	-	8.98E+00	-
Ethanol, passenger vehicle (PC)	-	-	-	-	7.27E+00
Electricity from coal ZA	-1.70E+02	-1.70E+02	-5.33E+01	-6.47E+01	1.10E+03
Heat from coal ZA	4.24E+02	-1.32E+02	1.80E+03	-1.05E+03	2.26E+03
Gasoline ZA	4.85E+02	4.85E+02	4.85E+02	4.85E+02	-
Gasoline, passenger car (PC)	7.29E+00	7.29E+00	7.29E+00	7.29E+00	-
Coal tailings in landfill	-6.56E+01	-1.41E+03	4.08E+03	-2.89E+03	1.32E+04
Process sludge, kg VS basis	4.44E+00	1.38E+00	2.32E+00	2.20E+00	2.91E+00
Total of all processes	6.92E+02	-1.22E+03	6.34E+03	-3.50E+03	1.66E+04

Major process contributions for the Fresh Water Aquatic Toxicity potential (expressed in kg 1,4-DB equivalents) for SYSTEM 1

	MBE	MBE-HI	EE	EE-HI	E-FFV
Electricity from coal ZA	-2.17E+00	-2.17E+00	-6.82E-01	-8.27E-01	1.41E+01
Heat from coal ZA	2.55E+00	-7.93E-01	1.08E+01	-6.31E+00	1.36E+01
Gasoline ZA	9.98E+00	9.98E+00	9.98E+00	9.98E+00	-
Coal tailings in landfill U	-1.97E+01	-4.24E+02	1.23E+03	-8.68E+02	3.97E+03
Coal from underground mine ZA	-3.36E-02	-4.85E-01	1.36E+00	-9.82E-01	4.44E+00
Total of all processes	-9.37E+00	-4.17E+02	1.25E+03	-8.67E+02	4.00E+03

Major process contributions for the Photochemical Oxidation potential; (expressed in kg C_2H_4 equivalents) for SYSTEM 1

	MBE	MBE-HI	EE	EE-HI	E-FFV
Bio-energy production	1.02E+00	3.16E-01	-	-	-
Electricity from bio-energy	1.85E-01	5.72E-02	4.98E-01	1.97E-01	-
Heat from bio-energy	-	4.28E-04	-	2.67E-01	-
Ethanol, passenger vehicle (PC)	-	-	-	-	3.86E+00
Electricity from coal ZA	-9.46E-01	-9.46E-01	-2.97E-01	-3.61E-01	6.14E+00
Heat from coal ZA	8.24E-01	-2.56E-01	3.50E+00	-2.04E+00	4.40E+00
Gasoline ZA	1.06E+00	1.06E+00	1.06E+00	1.06E+00	-
Gasoline, passenger car (PC)	3.86E+00	3.86E+00	3.86E+00	3.86E+00	-
Coal from underground mine ZA	-4.05E-03	-5.86E-02	1.64E-01	-1.19E-01	5.36E-01
Process sludge, kg VS basis	5.58E+00	1.73E+00	2.92E+00	2.76E+00	3.65E+00
Total of all processes	1.16E+01	5.78E+00	1.17E+01	5.64E+00	1.86E+01

Major process contributions for Acidification potential (expressed in kg SO_2 equivalents) for SYSTEM 1

	MBE	MBE-HI	EE	EE-HI	E-FFV
Electricity from bio-energy	2.81E+00	8.66E-01	6.37E+00	2.52E+00	-
Heat from bio-energy	-	6.47E-03	-	3.41E+00	-
Ethanol, passenger car (PC)	-	-	-	-	2.53E+00
Electricity from coal ZA	-2.78E+01	-2.78E+01	-8.73E+00	-1.06E+01	1.80E+02
Heat from coal ZA	2.29E+01	-7.10E+00	9.70E+01	-5.65E+01	1.22E+02
Gasoline ZA	2.62E+01	2.62E+01	2.62E+01	2.62E+01	-
Gasoline, passenger car (PC)	2.75E+00	2.75E+00	2.75E+00	2.75E+00	-
Total of all processes	2.68E+01	-5.06E+00	1.24E+02	-3.22E+01	3.05E+02

Major process contributions for Eutrophication potential (expressed in kg PO_4 equivalents) for SYSTEM 1

	MBE	MBE-HI	EE	EE-HI	E-FFV
Electricity from bio-energy	6.91E-01	2.13E-01	1.66E+00	6.56E-01	-
Heat from bio-energy	-	1.59E-03	-	8.87E-01	-
Ethanol, passenger car (PC)	-	-	-	-	6.38E-01
Electricity from coal ZA	-1.27E+00	-1.27E+00	-3.98E-01	-4.83E-01	8.23E+00
Heat from coal ZA	7.36E-01	-2.29E-01	3.12E+00	-1.82E+00	3.93E+00
Gasoline ZA	8.48E-01	8.48E-01	8.48E-01	8.48E-01	-
Gasoline, passenger car (PC)	6.38E-01	6.38E-01	6.38E-01	6.38E-01	-
Coal tailings in landfill	-1.08E-02	-2.33E-01	6.73E-01	-4.77E-01	2.18E+00
Total of all processes	1.64E+00	-2.74E-02	6.54E+00	2.49E-01	1.50E+01

SYSTEM 2: Summary of major energy flow for system expansion

		MBE	MBE-HI	CBE	CBE-HI
Electricity from WPS	***kWh***	1.13E+04	1.13E+04	**1.53E+04**	**1.53E+04**
Coal added for production for power generation scenarios	***kWh***	0	0	0	0
	MJ	1.14E+04	0	1.55E+04	0
Coal-based energy added for system expansion	***kWh***	3.99E+03	3.99E+03	0	0
Inherent energy of coal	***MJ***	1.41E+04	1.41E+04	0	0
Coal added	***kg***	1.89E+03	1.89E+03	0	0

SYSTEM 2: Impact category results

Major process contributions for the Global Warming (GWP) potential (expressed in kg CO_2 equivalents) for bio-methane system

	MBE	MBE-HI	CBE	CBE-HI
Biogas production	4.24E+03	1.32E+03	5.73E+03	1.94E+03
Electricity from biogas	2.76E+03	8.52E+02	3.74E+03	1.17E+03
Heat from biogas	-	6.37E+00	-	9.38E+01
Electricity from coal ZA	4.80E+03	4.80E+03	-	-
Heat from coal ZA	2.45E+03	-7.62E+02	3.32E+03	-1.12E+03
Coal from underground mine ZA	3.94E+02	1.85E+02	2.16E+02	-7.30E+01
Process sludge, kg VS basis	3.26E+04	1.73E+04	4.98E+04	2.90E+04
Total of all processes	4.73E+04	2.37E+04	6.28E+04	3.10E+04

Major process contributions for Human Toxicity potential (expressed in kg 1,4-DB equivalents) for bio-methane system

	MBE	MBE-HI	CBE	CBE-HI
Electricity from biogas	6.39E+00	1.97E+00	8.65E+00	2.71E+00
Heat from biogas	-	1.47E-02	-	2.17E-01
Electricity from coal ZA	2.15E+02	2.15E+02	-	-
Heat from coal ZA	4.24E+02	-1.32E+02	5.74E+02	-1.94E+02
Coal tailings in landfill	2.54E+03	1.19E+03	1.39E+03	-4.70E+02
Process sludge, kg VS basis	6.52E+00	3.46E+00	9.95E+00	5.80E+00
Total of all processes	3.19E+03	1.28E+03	1.98E+03	-6.55E+02

Major process contributions for the Fresh Water Aquatic Toxicity potential (expressed in kg 1,4-DB equivalents) for bio-methane system

	MBE	MBE-HI	CBE	CBE-HI
Electricity from coal ZA	2.75E+00	2.75E+00	-	-
Heat from coal ZA	2.55E+00	-7.93E-01	3.45E+00	-1.17E+00
Coal tailings in landfill	7.62E+02	3.58E+02	4.17E+02	-1.41E+02
Coal from underground mine ZA	8.52E-01	4.00E-01	4.66E-01	-1.58E-01
Total of all processes	7.68E+02	3.60E+02	4.21E+02	-1.42E+02

Major process contributions for the Photochemical Oxidation potential; (expressed in kg C_2H_4 equivalents) for bio-methane system

	MBE	MBE-HI	CBE	CBE-HI
Biogas production	1.02E+00	3.16E-01	1.37E+00	4.65E-01
Electricity from biogas	1.85E-01	5.72E-02	2.51E-01	7.86E-02
Heat from biogas	-	4.28E-04	-	6.30E-03
Electricity from coal ZA	1.20E+00	1.20E+00	-	-
Heat from coal ZA	8.24E-01	-2.56E-01	1.12E+00	-3.77E-01
Coal from underground mine ZA	1.03E-01	4.83E-02	5.63E-02	-1.90E-02
Process sludge, kg VS basis	8.18E+00	4.34E+00	1.25E+01	7.29E+00
Total of all processes	1.15E+01	5.70E+00	1.53E+01	7.44E+00

Major process contributions for Acidification potential (expressed in kg SO_2 equivalents) for bio-methane system

	MBE	MBE-HI	CBE	CBE-HI
Electricity from biogas	2.81E+00	8.66E-01	3.80E+00	1.19E+00
Heat from biogas	-	6.47E-03	-	9.54E-02
Electricity from coal ZA	3.52E+01	3.52E+01	-	-
Heat from coal ZA	2.29E+01	-7.10E+00	3.09E+01	-1.05E+01
Total of all processes	6.08E+01	2.89E+01	3.47E+01	-9.17E+00

Major process contributions for Eutrophication potential (expressed in kg PO_4 equivalents) for bio-methane system

	MBE	MBE-HI	CBE	CBE-HI
Electricity from biogas	6.91E-01	2.13E-01	9.35E-01	2.93E-01
Heat from biogas	-	1.59E-03	-	2.35E-02
Electricity from coal ZA	1.60E+00	1.60E+00	-	-
Heat from coal ZA	7.36E-01	-2.29E-01	9.96E-01	-3.37E-01
Coal tailings in landfill	4.19E-01	1.97E-01	2.29E-01	-7.75E-02
Total of all processes	3.45E+00	1.79E+00	2.16E+00	-9.80E-02

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